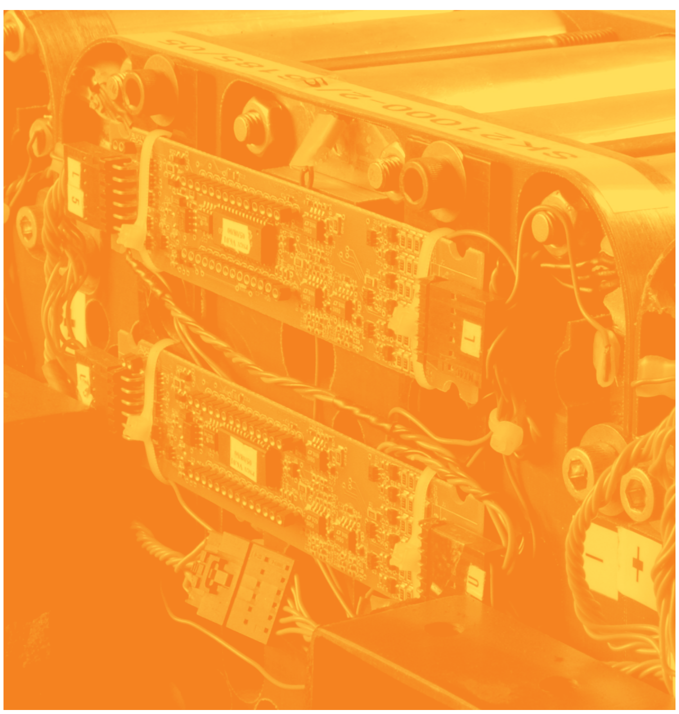
ENERGY STORAGE GRAND CHALLENGE

U.S. DEPARTMENT OF ENERGY

ROADMAP

DECEMBER 2020



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The Energy Storage Grand Challenge (ESGC) is a crosscutting effort managed by the U.S. Department of Energy's Research Technology Investment Committee (RTIC). This Roadmap was developed by the Energy Storage Subcommittee of the RTIC, co-chaired by Alex Fitzsimmons, Deputy Assistant Secretary for Energy Efficiency in the Office of Energy Efficiency and Renewable Energy (EERE), and Michael Pesin, Deputy Assistant Secretary for Advanced Grid Research and Development in the Office of Electricity (OE).

Significant contributions to the Roadmap were made by a technical team throughout the Department and at the National Laboratories. This included the ESGC Track Leads:

Technology Development Track—Eric Hsieh, OE

Manufacturing and Supply Chain Track—Valri Lightner, EERE

Technology Transition Track—Marcos Gonzales Harsha, Office of Technology Transitions (OTT)

Policy and Valuation Track—Alejandro Moreno, EERE

Workforce Development Track—John Vetrano, Office of Science (SC)

Additional contributors included Diana Bauer, Joe Cresko, Tina Kaarsberg, Sarah Garman, Paul Spitsen, Paul Syers, Steven Shooter, Changwon Suh, Alexis McKittrick, Karma Sawyer, Mary Hubbard, Nelson James, Sven Mumme Avi Shultz, Eric Miller, David Peterson, Steven Boyd, Mallory Clites, Peter Faguy, Ramesh Talreja, Lauren Ruedy, Rob Sandoli, and Rajesh Dham of EERE; Stephen Hendrickson, Katherine Harsanyi, and Rima Oueid of OTT; Ping Ge of SC; Vinod Siberry and Benjamin Shrager of OE; Bhima Sastri of the Office of Fossil Energy; Rebecca Onuschak, Alison Hahn, and Kelly Lefler of the Office of Nuclear Energy; Hugh Ho of the Office of Strategic Planning and Policy; Vikram Linga and Chris Namovicz of the Energy Information Administration; Monique Fridell of the Loan Programs Office; Scott Litzelman of the Advanced Research Projects Agency–Energy; Briggs White of the National Energy Technology Laboratory; Robert Podgorney of Idaho National Laboratory; and Vince Sprenkle of Pacific Northwest National Laboratory.

List of Acronyms

AC	alternating current
AMO	Advanced Manufacturing Office
ANL	Argonne National Laboratory
ARPA-E	Advanced Research Projects Agency-Energy
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATES	aquifer thermal energy storage
BES	Office of Basic Energy Sciences
BESS	battery energy storage technologies
BTES	borehole thermal energy storage
BTO	Building Technologies Office
BTU	British thermal unit
CAES	compressed air energy storage
CCUS	coal capture utilization and storage
CESER	Office of Cybersecurity, Energy Security and Emergency Response
CHP	combined heat and power
CSP	concentrating solar-thermal power
DAYS	Duration Addition to electricitY Storage program
DC	direct current
DER	distributed energy resource
DOE	Department of Energy
DPUTB	dual purpose underground thermal battery
DR	demand response
EEI	Edison Electric Institute
EERE	Office of Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
EPRI	Electric Power Research Institute
ESA	Energy Storage Association
ESGC	Energy Storage Grand Challenge
ESIF	Energy Systems Integration Facility
ESS	energy storage systems
EV	electric vehicle
FCAB	Federal Consortium for Advanced Batteries
FE	Office of Fossil Energy
FERC	Federal Energy Regulatory Commission
FOA	funding opportunity announcement
GMLC	Grid Modernization Laboratory Consortium
GRIDS	Grid-scale Rampable Intermittent Dispatchable Storage
GTO	Geothermal Technologies Office
GW	gigawatts
HEMS	home energy management system
HES	hydrogen energy storage
HFTO	Hydrogen and Fuel Cell Technologies Office
HTE	high-temperature electrolysis

HVAC	heating, ventilation, air conditioning
IECC	International Energy Conservation Code
IEI	Institute for Electric Innovation
INL	Idaho National Laboratory
IONICS	Integration and Optimization of Novel Ion-Conducting Solids
IP	intellectual property
IRS	Internal Revenue Service
ISO	Independent System Operators
JCESR	Joint Center for Energy Storage Research
LAES	liquid air energy storage
LBNL	Lawrence Berkeley National Laboratory
LCO	levelized cost of ownership
LCOE	levelized cost of energy
LCOS	levelized cost of storage
LCOSS	levelized cost of solar plus storage
LDRD	Laboratory Directed Research and Development
LHV	lower heating value
LPO	Loan Programs Office
MCH	methylcyclohexane
MRL	Manufacturing Readiness Level
MSP	minimum sustainable price
MW	megawatt
NARUC	National Association of Regulatory Utility Commissioners
NASEO	National Association of State Energy Officials
NE	Office of Nuclear Energy
NERC	North American Electric Reliability Corporation
NETL	National Energy Technology Laboratory
NREL	National Renewable Energy Laboratory
OE	Office of Electricity
ORNL	Oak Ridge National Laboratory
OTT	Office of Technology Transitions
PCM	phase change materials
PE	power electronics
PEC	photoelectrochemical
PEM	proton exchange membrane
PES	power electronic system
PNNL	Pacific Northwest National Laboratory
PSH	pumped storage hydropower
PUC	Public Utility Commission
PV	photovoltaics
RFB	redox-flow battery
RFC	reversible fuel cells
RFI	request for information
ROI	return on investment
RTE	roundtrip efficiency

RTES	reservoir thermal energy storage
RTIC	Research Technology Investment Committee
RTO	Regional Transmission Organization
SC	Office of Science
SETO	Solar Energy Technologies Office
SMR	steam methane reforming
SNL	Sandia National Laboratories
STCH	solar thermochemical hydrogen
STH	solar-to-hydrogen
TA	technical assistance
TCL	thermostatically controlled loads
TES	thermal energy storage
TOU	time-of-use
UPS	uninterruptible power supplies
VRE	variable renewable energy
VTO	Vehicle Technologies Office
WETO	Wind Energy Technologies Office
WPTO	Water Power Technologies Office

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Executive Summary

The Department of Energy's (DOE) Energy Storage Grand Challenge (ESGC) is a comprehensive program to accelerate the development, commercialization, and utilization of next-generation energy storage technologies and sustain American global leadership in energy storage.

Over the last four fiscal years (FY17–20), DOE has invested over $1.6 billion into energy storage research and development, or $400 million per year, on average. While technology offices have established individual goals and targets, the Department has never had a comprehensive strategy to address energy storage. This is why the U.S. Secretary of Energy announced the Energy Storage Grand Challenge in January 2020.

This comprehensive set of solutions requires concerted action, guided by an aggressive goal: to develop and domestically manufacture energy storage technologies that can meet all U.S. market demands by 2030.

This overarching goal is underpinned by three strategic goals tied to DOE's approach to the Challenge: Innovate Here, Make Here, Deploy Everywhere. In turn, the strategic goals are supported by quantitative targets. Recognizing the breadth of storage technologies and the ambitious nature of the goal, DOE has identified initial aggressive cost targets—highlighted in this Roadmap—that are focused on markets of significant size with substantial growth potential. Initial focal targets include:

- $0.05/kWh levelized cost of storage for long-duration stationary applications, a 90% reduction from 2020 baseline costs by 2030. [1,2,3] Achieving this levelized cost target would facilitate commercial viability for storage across wide a range of uses including:
    - Meeting load during periods of peak demand
    - Grid preparation for fast charging of electric vehicles
    - Applications to ensure reliability of critical infrastructures, including communications and information technology.
- $80/kWh manufactured cost for a battery pack by 2030 for a 300-mile range electric vehicle, a 44% reduction from the current cost of $143 per rated kWh.[4] Achieving this cost target would lead to cost-competitive electric vehicles.

[1] The levelized cost of storage (LCOS) is a function of a storage asset's capital and operating costs as well as its operational profile and energy output over its useful lifetime. Because LCOS has multiple drivers, meeting the ESGC's LCOS goal can be accomplished in multiple ways. For example, economies of scale can reduce capital costs, improved manufacturing processes and materials can increase asset lifespan, and/or new sensors and software can optimize the operation of the system while minimizing maintenance and reducing operating costs.

[2] Long-duration storage refers to systems capable of providing storage for more than 10 hours.

[3] Baseline cost estimates assume a 100 MW-10 hour system and come from the 2020 Grid Energy Storage Technology Cost and Performance Assessment (DOE/PA-0204), Kendall Mongird, Vilayanur Viswanathan, Jan Alam, Charlie Vartanian, and Vincent Sprenkle, Pacific Northwest National Laboratory; and Richard Baxter, Mustang Prairie Energy.

[4] Current performance is for lithium ion cells; however future targets may be met by other chemistries such as lithium metal.

- Advances in battery production for transportation applications are anticipated to continue benefitting production, performance, and safety of similar technologies used in batteries for stationary applications.

DOE recognizes that both operational cost and manufacturing cost declines are required to enable domestic manufacturers to produce technologies that are cost competitive. As markets evolve and R&D advances, the ESGC will refine these focal targets as well as other cost and performance targets, presented later in the Roadmap, for additional energy storage applications.

DOE is taking a holistic approach to meet the ESGC goal by establishing five tracks, starting with fundamental R&D for storage technologies and following through to production and deployment.

- The Technology Development Track aligns DOE's ongoing and future energy storage R&D around Use Cases and long-term leadership.
- The Manufacturing and Supply Chain Track will develop technologies, approaches, and strategies for U.S. manufacturing that support and strengthen U.S. leadership in innovation and continued at-scale manufacturing.
- The Technology Transition Track will work to ensure that DOE's R&D transitions to markets through field validation, demonstration projects, public-private partnerships, bankable business model development, and the dissemination of high-quality market data.
- The Policy and Valuation Track will provide data, tools, and analysis to support policy decisions and maximize the value of energy storage.
- The Workforce Development Track will educate the workforce, who can then research, develop, design, manufacture, and operate energy storage systems.

DOE will track progress relying both on manufacturing targets as well as production cost and performance targets. Success metrics within the Policy and Valuation, Technology Transition, and Workforce Tracks will serve to complement the interrelated technology and manufacturing targets.

The pages that follow outline DOE's Roadmap. DOE previously released a draft version of this Roadmap in July 2020 along with a Request for Information (RFI). The Department reviewed the comments from stakeholders and made updates and modifications to the Roadmap based on this feedback.

Through the ESGC, the Department will deploy its extensive resources and expertise to address the technology development, commercialization, manufacturing, valuation, and workforce challenges to position the United States for global leadership in the energy storage technologies of the future.

Overview

The ESGC seeks to create and sustain American leadership in energy storage. While research and development (R&D) is the foundation of advancing energy storage technologies, the Department recognizes that leadership in a global marketplace also requires addressing associated challenges: to transition technologies from the lab to the marketplace; to manufacture technologies at scale in the United States; and to secure supply chains.

This Roadmap focuses on three key challenges, applied to each of the five tracks, to ensure that the United States sustains global leadership in energy storage:

- **Innovate Here** – How can DOE enable the United States to lead in energy storage R&D and retain intellectual property (IP) developed through DOE investment in the United States?
- **Make Here** – How can DOE work to lower the cost and energy impact of manufacturing storage technologies, and strengthen domestic supply chains by reducing dependence on foreign sources of materials and components?
- **Deploy Everywhere** – How can DOE work with relevant stakeholders to develop technologies that meet our domestic usage needs and enable the United States to deploy technologies in domestic markets and export energy storage products and services around the world?

ESGC Structure

The Roadmap outlines a comprehensive department-wide strategy to drive significant advancements in R&D across the wide range of storage technologies and to address critical barriers to development and deployment at scale. DOE is taking a holistic approach to energy storage that incorporates five tracks, starting with fundamental R&D for storage technologies and following through to production and deployment.

- The Technology Development Track will focus DOE's ongoing and future energy storage R&D around user-centric Use Cases and long-term leadership.
- The Manufacturing and Supply Chain Track will develop technologies, approaches, and strategies for U.S. manufacturing that support and strengthen U.S. leadership in innovation and continued at-scale manufacturing.
- The Technology Transition Track will work to ensure that DOE's R&D transitions to domestic markets through field validation, demonstration projects, public-private partnerships, bankable business model development, and the dissemination of high-quality market data.
- The Policy and Valuation Track will provide data, tools, and analysis to support policy decisions and maximize the value of energy storage.
- The Workforce Development Track will educate the workforce, who can then research, develop, design, manufacture, and operate energy storage systems.

Technology Development Track

The Technology Development Track will focus DOE's ongoing and future energy storage R&D around user-centric goals and long-term leadership. This R&D strategy consists of three components: Use Cases; technology portfolios; and development pathways.

First, a set of guiding Use Cases identifies energy storage uses, benefits, and functional requirements for 2030 and beyond. The ESGC proposes six Use Cases as guidepost examples that envision long-term ways in which energy storage can benefit end users. The Use Cases, with their associated performance and cost targets, will be updated through a periodic stakeholder process.

Second, the ESGC will continue DOE's efforts to advance a diverse technology portfolio with the potential to meet the functions identified in the Use Cases. The Use Cases help to specify performance goals, including characteristics such as a system's lifetime, mobility, and efficiency. These goals could be achieved through any number of technology pathways, which have the ability to meet the needs of one or more Use Cases, including the ESGC groupings of Bidirectional Electrical Storage; Thermal and Chemical Storage; and Flexible Generation and Load.

Finally, the ESGC will leverage DOE and industry capabilities to accelerate the pathway to commercialization. The ESGC will map the network of DOE and industry capabilities, such as consortia, partnerships, and test facilities, to structure an ecosystem that, in partnership with industry, will achieve improved energy storage systems to solve ambitious challenges.

Manufacturing and Supply Chain Track

The Manufacturing and Supply Chain (M&SC) Track will work to strengthen the domestic production of energy storage technologies by accelerating the scale-up of innovations produced by the successes of the Technology Development Track, lowering the cost of manufacturing energy storage technologies, and decreasing reliance on foreign sources of critical materials. To accomplish these goals, the M&SC Track will pursue six types of activities, in coordination with industry and other federal agencies.

First, the M&SC Track will work to improve understanding of shared technical barriers, conducting detailed studies of manufacturing processes for specific storage technologies and obtaining feedback from industry.

Second, this track will coordinate R&D investments across DOE to help domestic researchers and manufacturers innovate reduce manufacturing cost and overcome the shared technical barriers in production and manufacturing. Third, this track will support accelerated scale-up of emerging manufacturing processes by expanding U.S. capabilities for testing and validating manufacturing innovations at National Laboratories and other facilities and making these facilities available to innovators. Fourth, this track will standardize storage system design and evaluation protocols to streamline integration of manufacturing innovations.

Fifth, the track will pursue critical materials supply chain resilience by addressing supply chain risks in an integrated fashion in collaboration with other agencies as part of the Federal Strategy on Critical Minerals.

Finally, in support of the goals of this track, the Department joined with the Department of Commerce, the Department of Defense, and the Department of State to form the Federal Consortium for Advanced Batteries (FCAB)[5] to foster executive level strategic alignment, coordination, and collaboration across

5 https://www.energy.gov/eere/vehicles/downloads/federal-consortium-advanced-batteries

the federal agencies to establish a domestic battery materials and technology manufacturing ecosystem that serves commercial and military applications.

Technology Transition Track

The Technology Transition Track will strengthen U.S. leadership in energy storage through the commercialization of energy storage innovations. This will be accomplished through the development of proactive field validation, public-private partnerships, bankable business models, financing, technology standards, pro forma contracts, and the dissemination of high-quality market data. These mechanisms will enable the commercialization, private sector financing, and deployment of energy storage technologies. Such work gives market participants confidence that an energy storage asset will perform to expectations and have market demand, thus reducing production or project risk, lowering project costs, increasing investment, and accelerating scalable deployment.

Policy and Valuation Track

The Policy and Valuation Track will provide data, tools, and technical analysis that help maximize the value of energy storage to the power, industrial, and transportation systems, driving U.S. leadership in the innovation, manufacturing, and deployment of energy storage technologies. While other ESGC tracks support energy storage technologies and projects, the Policy and Valuation Track focuses on providing support to decision-makers, who are looking to optimize the power or energy system as a whole. The track will leverage the Department’s unique analytical capabilities, data, and computing resources to enhance the technical characterization of energy storage technologies, develop more sophisticated tools, and deliver a program of systematic, coordinated institutional support targeting key stakeholder needs. The track will be continuously updated and informed by the evolving challenges and concerns of the policy, regulatory, and planning bodies who need them most.

Workforce Development Track

The Workforce Development Track will focus DOE’s technical education and workforce development programs to leverage existing resources to train and educate the workforce, who can then research, develop, design, manufacture, and operate energy storage systems widely within U.S. industry. To ensure a proper focus, DOE will continue to solicit feedback from relevant stakeholders on workforce development needs through ongoing stakeholder engagement across a broad spectrum of energy-storage related industries. DOE will assess existing education and workforce development programs in areas of energy storage and the related technologies to see where gaps or redundancies exist and where DOE may initiate, grow, or focus these programs. These opportunities span a wide range of educational and focus levels, from scientists to engineers to trades.

Background

In September 2018, Congress passed the Department of Energy Research and Innovation Act 115-246 (the Act). The Act directs the Secretary of Energy to “identify strategic opportunities for collaborative research, development, demonstration, and commercial application of innovative science and technologies" and "to promote collaboration and crosscutting approaches" and "prioritize activities that use all affordable domestic resources."[6]

Pursuant to the Act, the Department established the Research Technology Investment Committee (RTIC) to convene the key elements of DOE that support R&D activities, coordinate their strategic research priorities, and identify potential crosscutting opportunities in both basic and applied science and technology. The ESGC is a crosscutting effort managed by DOE's RTIC. The Energy Storage Subcommittee of the RTIC is co-chaired by the Office of Energy Efficiency and Renewable Energy (EERE) and the Office of Electricity (OE). In addition to EERE and OE, the Energy Storage Subcommittee includes the Office of Science, Office of Fossil Energy, Office of Nuclear Energy, Office of Technology Transitions, Advanced Research Projects Agency–Energy, Office of Strategic Planning and Policy, the Loan Programs Office, and the Office of the Chief Financial Officer.

The ESGC focuses resources from across the Department to create a comprehensive program to accelerate the development and commercialization of next-generation energy storage technologies and sustain U.S. global leadership in energy storage. As summarized below, DOE's individual offices conduct a range of storage activities. A more detailed summary of how DOE offices support these technologies can be found in Appendix 3.

Office of Science (SC): Supports basic research that underpins a wide range of current and potential technologies for energy storage. The office also supports a range of user facilities such as light and neutron sources, supercomputers, and advanced synthesis capabilities that provide insight into operation of energy storage systems from the atomic scale to operating prototypes.

Advanced Research Projects Agency–Energy (ARPA-E): Advances energy storage technologies by focusing on early stage, high-impact technologies as well as activities to bring those technologies to the market, including techno-economic analysis, stakeholder outreach, and technology-to-market plans. Examples of current activities include Grid-scale Rampable Intermittent Dispatchable Storage (GRIDS), Integration and Optimization of Novel Ion-Conducting Solids (IONICS), Duration Addition to electricitY Storage (DAYS), and ARPA-E's OPEN Funding Opportunity Announcements.

Office of Electricity (OE): Focuses on grid-scale bidirectional electrical storage. Within OE, both the Energy Storage program and the Transformer Resilience and Advanced Components (TRAC) program support ESGC objectives. The OE Energy Storage program includes focus areas in Energy Storage Technology Development, Safety and Reliability, and Energy Storage Analytics. The OE TRAC program addresses innovative designs, materials research, and exploratory concepts, as well as modeling and analysis to address the range of challenges associated with transformers and other grid components, including the power conversion equipment used by energy storage.

Energy Efficiency and Renewable Energy (EERE): Supports energy storage R&D, both for stationary and mobility applications. This includes leading the Department's applied R&D on lithium-ion batteries, pumped storage hydropower, and hydrogen and fuel cell technologies, as well as increased power system flexibility from thermal storage, renewable energy generation, and controllable loads. EERE also supports manufacturing research to lower the manufacturing cost and improve performance of storage

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6 https://www.congress.gov/115/plaws/publ246/PLAW-115publ246.pdf

technologies. In addition, EERE supports analytical efforts to examine the role of storage in the power system and provides storage-related technical assistance to policy makers and facility owners.

Office of Fossil Energy (FE): Leads work advancing a range of thermal, chemical, hydrogen, and battery energy storage technologies and integrating them with fossil-based assets to improve asset flexibility, grid reliability, and environmental performance. FE also supports analytical work and stakeholder engagements to define technology requirements, metrics, and barriers to energy storage deployment.

Office of Nuclear Energy (NE): Supports integrated energy systems R&D, which explores coupling electrical, thermal, and chemical storage systems with nuclear power and other generation types to enable clean, affordable, reliable, and resilient energy systems. The NE system modeling, simulation, and technology development efforts seek to optimize technical and economic performance in commercial applications.

Office of Technology Transitions (OTT): Advances the economic, energy, and national security interests of the United States by expanding the commercial impact of the DOE's research and development portfolio. It streamlines access to information and to DOE's National Labs and facilities—fostering partnerships that guide innovations from the lab into the marketplace and address barriers to commercialization.

Energy Storage Technologies Included in the ESGC

Energy Storage includes a broad range of technologies that fall into two basic categories: potential energy and kinetic energy. Potential energy is stored energy and the energy of position, and includes chemical, mechanical, and gravitational energy. Kinetic energy is the motion of waves, electrons, atoms, molecules, substances, and objects, and includes thermal, motion, and electrical energy.[7]

As shown in Figure 1, the ESGC groups storage technologies into three focus areas:

- Bidirectional electrical storage (stationary and mobile)
- Chemical and thermal storage
- Flexible generation and controllable loads.

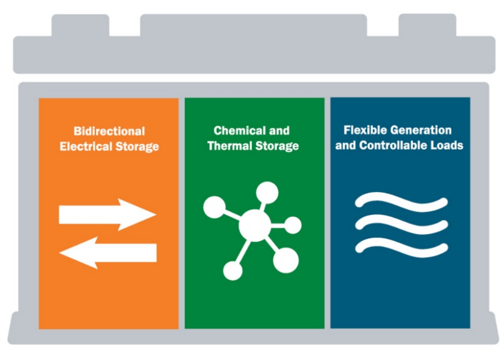

Figure 1. Categories of storage included in the Energy Storage Grand Challenge

7 https://www.eia.gov/energyexplained/what-is-energy/forms-of-energy.php

In addition to the storage medium itself, power conversion equipment is a major component of most energy storage systems and is included in the ESGC. More detailed information on these technologies can be found in Appendix 3.

Bidirectional Electrical Storage includes technologies and systems that are capable of absorbing electric energy, storing that energy for a period of time, and dispatching the stored energy in the form of electricity. They include the following classes of technologies: electrochemical, mechanical, and electrical storage. Electrochemical storage systems use chemical reactions to convert and store energy, encompassing a range of battery chemistries and designs for stationary and transportation applications. Mechanical storage systems use mechanical methods to convert and store electrical energy. These systems include pumped water, compressed air, spinning flywheels, and emerging gravity storage systems. Electrical storage systems store electrical energy directly using specialized materials including capacitors and superconducting magnetic coils. Thermal and chemical energy storage systems can also be used for bidirectional electrical storage by using electricity to charge the thermal or chemical reservoir and discharging, on demand, through a heat engine, fuel cell, or other power conversion device.

Chemical and Thermal Energy Storage focuses on the media and containment technologies not included in other categories that are capable of harnessing chemical or thermal energy for conversion to or from electricity. Thermal energy storage technologies include high-temperature reservoirs such as molten salt, phase change materials, concrete, and geothermal resources as well as lower temperature storage, including additional geothermal applications, phase change materials, and the thermal mass of buildings. These thermal reservoirs can be discharged to provide heat for a variety of applications, including electricity generation through a heat engine, industrial processes, or buildings uses.[8] Chemical energy storage includes hydrogen (e.g., compressed gaseous H_2 or cryogenic liquid H_2) and other energy-carrying chemicals produced from diverse domestic energy sources (e.g., renewables, nuclear, and fossil), enabling high energy density, long duration/seasonal storage, and the ability to couple and decouple from the grid in unique ways to address not only the power sector but industrial and transportation sectors. Hydrogen and other hydrogen-rich chemical energy carriers can be synthesized at industrial scales utilizing diverse domestic energy resources for subsequent use in various one-way energy storage applications (such as power-to-gas, power-to-liquids, steel manufacturing, and heavy-duty vehicles, among others), as well as bidirectional storage.

Flexible Generation and Controllable Loads include technologies, equipment, and systems capable of enhancing the flexibility of production or consumption resources. They include technologies that help power generation resources to start, stop, and adjust output more quickly, enable shifting of energy demand to better match generation, which can enhance the ability of energy resources to provide grid services. They also include the integration of dispersed load with storage and behind-the-meter generation, which can lower the overall load that manufacturers place on the grid.

Power Electronics (PE) refers to the broad set of technologies (e.g., materials, components, subsystems, and systems) necessary for the control and conversion of electricity. A *power electronic system* (PES) is a self-contained, fully functional collection of hardware and software that safely and efficiently converts

8 Because certain thermal energy storage applications can meet the relatively modest temperature requirements of space heating and cooling applications, they can also potentially offset demands on the grid that would otherwise manifest as electrical heating or cooling loads.

current-type (e.g., AC to DC, DC to AC), voltage (e.g., DC to DC), frequency (e.g., AC to AC), or any combination thereof, and conditions electric power according to application-specific requirements.

Mission, Vision and Goal

DOE is adept at R&D, but R&D is not sufficient for the United States to be the world leader in energy storage. While DOE has world-class researchers, efforts beyond DOE's mission scope are required to transition technology from the lab to the marketplace and to facilitate manufacturing at scale. This comprehensive set of solutions requires concerted action, supported by a bold mission, vision, and goal.

Mission: To be a global leader in energy storage innovation, manufacturing, and utilization.

Vision: Energy storage technologies enable a U.S. and global energy system that is resilient, flexible, affordable, and secure.

Goal: To develop and domestically manufacture energy storage technologies that can meet all marketplace demands by 2030.

The global demand for energy storage solutions across a range of applications is expected to increase to more than 2,500 GWh by 2030, four-fold from a 2018 baseline, creating enormous opportunity for American technology providers, manufacturers, other companies up and down the supply chain, and the broader economy, and workers.[9,10,11,12] This Roadmap outlines how DOE and more specifically how each ESGC Track will measure progress towards meeting specific objectives tied to the overarching goal.

Key Challenges and Strategic Goals

The ESGC focuses on three key challenges to ensure that the United States sustains global leadership in energy storage:

- **Innovate Here** – How can DOE enable the United States to lead in energy storage R&D and retain intellectual property developed through DOE investment in the United States?
- **Make Here** – How can DOE work to lower the cost and energy impact of manufacturing storage technologies and strengthen domestic supply chains by reducing dependence on foreign sources of materials and components?
- **Deploy Everywhere** – How can DOE work with relevant stakeholders to develop technologies that meet our domestic usage needs and enable the United States to not only successfully deploy technologies in domestic markets but also export technologies?

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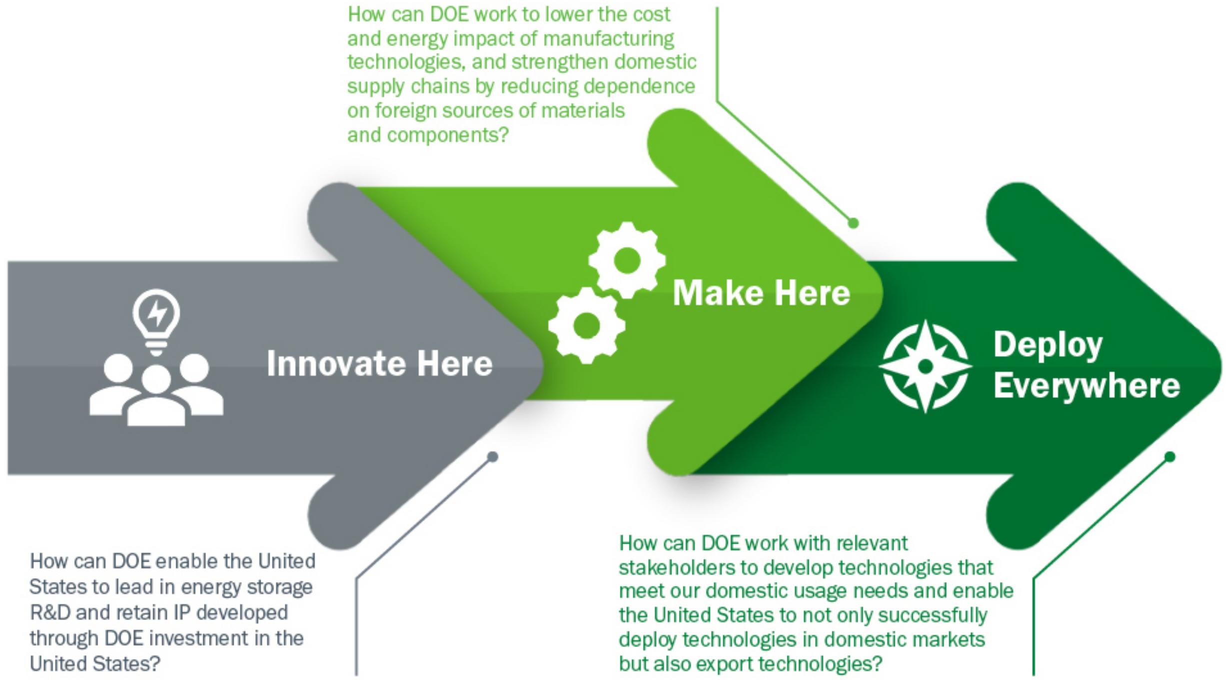
9 Bloomberg New Energy Finance, "Long-Term Electric Vehicle Outlook 2020," New York, 2020.

10 C. Pillot, "Lead Acid Battery Market," *Avicenne Energy*, Paris, 2019.

11 Bloomberg New Energy Finance, "2019 Long-Term Energy Storage Outlook," New York, 2019.

12 International Hydropower Association, The world's battery: Pumped hydropower storage and the clean energy transition, London, 2019.



The ESGC has developed a strategic goal corresponding to each challenge and also tied to the overarching ESGC Goal, "to develop and domestically manufacture energy storage technologies that can meet all marketplace demands by 2030."

Strategic Goals

1. **Innovate Here**: Develop a portfolio of technologies that are capable of cost-effectively serving all of the ESGC Use Cases by 2030.
2. **Make Here**: Catalyze cost-effective, domestic manufacturing capabilities and secure supply chains for a portfolio of energy storage technologies that can meet growing market demands.
3. **Deploy Everywhere**: Accelerate technology transition and market development in the United States and abroad to utilize the full range of American-made energy storage technologies.

Measuring Success

With the myriad of energy storage technologies and the range of Use Cases, defining success and tracking progress are not simple. Additionally, success in each track depends on and can build on the successes of the other tracks. Significant investment is required to develop new technologies, and the impact that those technologies can have on the public welfare relies heavily on the scale and efficiency with which they can be manufactured.

A fundamental relationship exists between unit cost and manufacturing volume capacity of any technology. Factories need properly trained people to run them, tying the production volume and quality of technologies to workforce training. Real-world market data is required to validate these R&D metrics and inform commercialization strategies. Together, cost, manufacturing, market and workforce metrics can inform national and local policies and support the rapid commercialization and deployment of energy storage technologies.

Recognizing the breadth of storage technologies and the ambitious nature of the goal, DOE has identified initial aggressive cost targets—highlighted in this Roadmap—that are focused on markets of significant size with substantial growth potential.[13] Initial focal targets include:

- $0.05/kWh levelized cost of storage for long-duration stationary applications, a 90% reduction from 2020 baseline costs by 2030. [14,15,16] Achieving this levelized cost target would facilitate commercial viability for storage across a wide range of uses including:
    - Meeting load during periods of peak demand
    - Grid preparation for fast charging of electric vehicles
    - Applications to ensure reliability of critical infrastructures, including communications and information technology.
- $80/kWh manufactured cost for a battery pack by 2030 for a 300-mile range electric vehicle, a 44% reduction from the current cost of $143 per rated kWh.[17] Achieving this cost target would lead to cost-competitive electric vehicles.
    - Advances in battery production for transportation applications are anticipated to continue benefitting production, performance, and safety of similar technologies used in batteries for stationary applications.

DOE recognizes that both operational cost and manufacturing cost declines are required to enable domestic manufacturers to produce technologies that are cost competitive. As markets evolve and R&D advances, the ESGC will refine these focal targets as well as other cost and performance targets for additional energy storage applications, presented later in this Roadmap.

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[13] Energy storage systems can provide a wide arrange of energy, capacity, transmission, and ancillary services. In order to assess the economics of energy storage technologies that can provide multiple services and shift energy across time, it is critical to use metrics that account for both value and cost. The specific metric used is often determined by the user's perspective and the use case the storage system is envisioned to fill. For example, an independent power producer considering energy storage might compare its life cycle costs to its life cycle revenue to ensure a satisfactory rate of return; a vertically integrated utility using a least-cost planning approach will look at the net present value or levelized cost of its entire system in order to capture value of the storage asset providing services and interacting with the rest of its system; a facility owner, if considering energy storage for backup power, may compare the cost of the storage system to the avoided costs of lost production due to outages or a back-up diesel generator. Because of this challenge, the ESGC will continue to report both the cost of energy storage technologies as well as develop metrics that describe the emerging value proposition of energy storage across a wide range of use cases.

[14] The levelized cost of storage (LCOS) is a function of a storage asset's capital and operating costs as well as its operational profile and energy output over its useful lifetime. Because LCOS has multiple drivers, meeting the ESGC's LCOS goal can be accomplished in multiple ways. For example, economies of scale can reduce capital costs, improved manufacturing processes and materials can increase asset lifespan, and/or new sensors and software can optimize the operation of the system while minimizing maintenance and reducing operating costs.

[15] Long-duration storage refers to systems capable of providing storage for more than 10 hours.

[16] Baseline cost estimates assume a 100 MW-10 hour system and come from the 2020 Grid Energy Storage Technology Cost and Performance Assessment (DOE/PA-0204), Kendall Mongird, Vilayanur Viswanathan, Jan Alam, Charlie Vartanian, and Vincent Sprenkle, Pacific Northwest National Laboratory; and Richard Baxter, Mustang Prairie Energy.

[17] Current performance is for lithium ion cells, however future targets may be met by other chemistries such as lithium metal.

In addition to these focal cost targets, each of the five ESGC tracks will assess progress as described below.

- The **Technology Development Track** will utilize common user-defined performance and cost metrics, applying to each Use Case. These application-aware targets are aimed at accelerating technology development to achieve commercial viability.
- The **Manufacturing and Supply Chain Track** will aim to advance manufacturing capabilities to achieve the target price goals established by the Technology Development Track. The M&SC Track will also follow the global energy storage markets using common industry metrics, such as U.S. manufacturing industry market share or U.S. production capacity and production output.
- The **Technology Transition Track** will develop and maintain real-world market metrics that inform the ESGC's commercialization efforts as well as the ESGC strategy overall. These metrics may include investment, project, and manufacturing data for the range of Use Cases and technologies within the ESGC scope. Market metrics can also help to identify new markets relevant to the ESGC. The real-world market data captured in these metrics can also validate and inform the strategy and activities of the other ESGC pillars.
- The **Policy and Valuation Track** will create and maintain an online energy storage cost and performance database that develops a standardized energy storage cost nomenclature, tracks current energy storage component and system costs, and estimates a range of future energy storage cost trajectories. These data can provide insights about the competitiveness of different energy storage technologies for a given Use Case. The track will also utilize cutting-edge modeling and analysis to assess the value and potential deployment of energy storage technologies in different Use Cases under future grid and market scenarios. Ultimately, the data, tools, and analysis in the Policy and Valuation Track can help inform the prioritization of research activities in other tracks.
- The **Workforce Development Track** will evaluate and track the needs of energy storage developers, manufacturers and those who deploy systems, maintaining and growing DOE's educational activities to ensure a viable workforce.

Technology Development

Track Overview

Purpose: Implement an R&D ecosystem that strengthens and maintains U.S. leadership in energy storage innovation through development of energy storage technologies capable of meeting all energy system requirements for storage and flexibility by 2030.

Need: The next generation of energy storage technologies will continue to deliver benefits extending to the grid, transportation, and throughout the economy. Proactive and coordinated DOE actions will be required to develop the new tools and technologies that accelerate energy storage development.

Mission: The ESGC will create a framework of capabilities and programs that maximize the pace of storage innovation through improved performance and decreased cost.

To help realize the vision of U.S. energy storage leadership, the Technology Development Track will establish user-centric Use Cases and technology pathways to guide near-term acceleration and long-term leadership in energy storage technologies. A set of energy storage Use Cases, enabled by aggressive cost reductions and performance improvements, will help guide R&D objectives across a diversity of storage and enabling technologies. A full description of the Use Case framework is discussed under Activities. After identifying a portfolio of technologies that have the potential to achieve major functional improvements, ensuring long-term leadership includes augmenting the R&D ecosystem to enable constant innovation. The storage ecosystem includes partnerships, consortia, infrastructure, and other long-term resources that accelerate the journey from concept to commercialization.

What is the role of government? What is DOE's role? The government's role is to invest in early stage research that poses too high a financial risk for the private sector. Time horizons in many businesses are short. Few companies are in a position to capture benefits from long-term fundamental research they might fund on their own. Fundamental research often requires resources available only to governments and the largest companies. Without government support for such research, the seed for the next generation of storage technology would be at risk.[18] Examples of market-transforming government-supported innovations from other industries include shale gas,[19] solar photovoltaic,[20] and vehicle propulsion technologies.[21] By providing support for early stage research and reducing the cost of technology validation, the government can accelerate the industry's ability to commercialize new innovative energy storage technologies. Creating a framework to align long-term market requirements with long-lead research programs will help maximize the effectiveness of government support throughout the R&D cycle.

[18] https://www.energy.gov/sites/prod/files/Sandalow%20innovation%20remarks%2010-21-11.pdf

[19] https://www.energy.gov/sites/prod/files/Sandalow%20innovation%20remarks%2010-21-11.pdf

[20] https://www.energy.gov/sites/prod/files/2015/05/f22/evaluating_realized_rd_mpacts_9-22-14.pdf

[21] https://www.energy.gov/sites/prod/files/2015/05/f22/evaluating_realized_rd_mpacts_9-22-14.pdf

Addressing Key Challenges through Technology Development

Innovate Here: The United States is already home to a rich ecosystem of energy storage innovators. U.S. universities (often funded by DOE) represent a major share of worldwide storage patents.[22] The ESGC will help align the outputs of this lab, academia, and industrial ecosystem so that more of these innovations will be made here and deployed here.

Impact

How can the Energy Storage Grand Challenge make a difference? By strengthening the connections between end user benefits and all research stages, the ESGC hopes to accelerate the entire innovation process. From basic research to demonstrations, ESGC activities will be structured to identify, as early as possible, the technologies with characteristics that match end user requirements, as encapsulated in the ESGC Use Cases.

Activities

This chapter serves as a working plan that explains the goals and organization of the ESGC Technology Development Track to a wide variety of stakeholders. The specific targets within each activity will evolve over time as DOE receives additional feedback from stakeholders.

Activity 1 Develop a set of stakeholder-informed Use Cases that identifies and updates technology-neutral performance and cost targets for 2030 and beyond.

Activity 2 Identify a portfolio of energy storage technologies that have an R&D pathway to achieve the cost targets by 2030. Develop standardized metrics that facilitate technology-agnostic cost and performance evaluations.

Activity 3 Support pathways (from fundamental research to pre-commercial demonstrations) of the U.S. innovation ecosystem (including National Labs, universities, start-ups) for all storage technologies.

Activity 1: Use Cases as Technology-Neutral Guideposts

Introduction to the ESGC Use Case Framework. A Use Case describes a set of broad or related future applications that could be enabled by much higher performing or lower cost energy storage. Each Use Case can contain multiple specific instances that represent scenarios ranging from early high-value projects to high-quantity mass adoption.

The Use Cases are intended as guidepost examples to facilitate stakeholder discussions that envision future (i.e., 2030 and beyond) ways in which energy storage can benefit end users. The ESGC will seek to identify specific regional and local examples in each Use Case to help validate the requirements and technical requirements for future energy storage systems.

Process. To assemble an initial set of Use Cases, DOE offices and labs were invited to submit future scenarios that could be enabled through a significant cost or performance improvement in storage technologies. These scenarios were assembled into six broad Use Case families presented in the Draft

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22 https://www.idtechex.com/en/research-report/advanced-energy-storage-technologies-patent-trends-and-company-positioning/271

Roadmap, and have been updated and revised taking into account input from the stakeholder workshops and responses to the RFI. These Version 1.0 Use Cases, with their associated functional requirements and performance and cost targets, will be updated through a periodic stakeholder process.

Use Case Structure. Each Use Case includes an identification of requirements and scope, a high-level vision statement of success for the Use Case, and identification of stakeholders and beneficiaries. Each also includes an identification of benefits and values, preliminary discussions of technical requirements, and examples of enabling technology pathways. Appendix 1 contains a full description of the six Use Cases. An overview of the Use Case families is provided in Table 1.

Table 1. Use Case scope

Use Case	Scope
1. Facilitating an Evolving Grid	The ability of the U.S. electric power system (i.e., the electric grid) to reliably meet customer demand is crucial to our economy and national security. The increasing adoption of variable renewable energy (VRE) and dynamic changes in customer demand, as well as stresses from weather, physical, and cyber threats, highlight how enhanced grid flexibility can ensure the continued reliability, resilience, and security of the electric power system.
2. Serving Remote Communities	Up to a billion people in the world do not have access to electricity. Island, coastal, and remote communities that are disconnected from the bulk power system pay a premium for electricity due to fuel logistics and maintenance associated with diesel generation. In remote communities subject to extreme weather conditions, fuel supply disruptions are a major risk factor.
3. Electrified Mobility	Increasing electrification in in the transportation sector can be facilitated with large-scale, reliable, high-power, and cost-effective charging infrastructure that enables charging times equivalent to that of refueling at a traditional gas station. Because high-power DC fast charging can stress the delivery capacity of the local distribution grid, this new charging infrastructure should minimize any negative grid impact and optimize operations with the grid and other end uses, including buildings. Beyond charging infrastructure, energy storage systems will also be necessary for the electric vehicles themselves. Lower manufacturing costs and improved performance of domestically produced electric vehicle batteries can facilitate widespread adoption and further establish American leadership in energy storage.
4. Interdependent Network Infrastructure	The operation of the electric grid depends on other infrastructure sectors, including natural gas, communications, information technology, water, and financial services. Loss of function and service within this infrastructure due to energy delivery disruption can have far-reaching impacts and costs for end users. These interdependencies elevate the importance of sustaining the normal operations of critical infrastructure amidst short-term disruption of energy inputs.

Use Case	Scope
5. Critical Services	Sectors that provide critical services include the defense industrial base sector, emergency services sector, government facilities sector, and health care and public health sector. An extended loss of power to facilities in these sectors could lead to unacceptable public health and safety risks, especially following disaster-related power outages. Similarly, many companies or manufacturers require the ability to resume and maintain operations in the event of an extended outage. The importance of these services reinforces the importance of sufficient energy supplies to these facilities during an extended outage.
6a. Facility Flexibility, Efficiency, and Value Enhancement: Commercial and Residential Buildings	This Use Case seeks to leverage opportunities to optimize energy production and usage in facilities, especially commercial and residential buildings. Optimized integrated processes can utilize high-performance, low-cost energy storage technologies to enhance the overall facility value to the owner, operator, and ultimately, the end consumer.
6b. Facility Flexibility, Efficiency, and Value Enhancement: Energy Intensive Facilities	This Use Case seeks to leverage opportunities to integrate energy storage within a range of electric power generation and energy-intensive industrial facilities. This sub-family is characterized by significantly higher energy flows than the commercial/residential buildings sector. The nature of how energy is converted and transported in the processes associated with energy-intensive facilities optimization offers potential opportunities for improvement in economics, flexibility, and market diversity.

Figure 2 plots each Use Case by its location within the electricity system and the degree to which the anticipated benefits are easy to quantify or define. In this discussion, the electricity system includes generation, transmission, distribution, end use, and transportation as a connected system. Off-grid applications are also within the ESGC scope, as part of “Serving Remote Communities.” Some anticipated benefits, such as energy arbitrage and demand charges, have relatively well-defined values today, such as in “Facility Flexibility,” “Facilitating an Evolving Grid,” and “Electrified Mobility.” Other benefits, such as resilience, have less well-defined values, such as in “Interdependent Network Infrastructure” and “Critical Services.” Developing and identifying these values, and in turn informing the cost targets for technology R&D, are part of the Policy and Valuation Track.

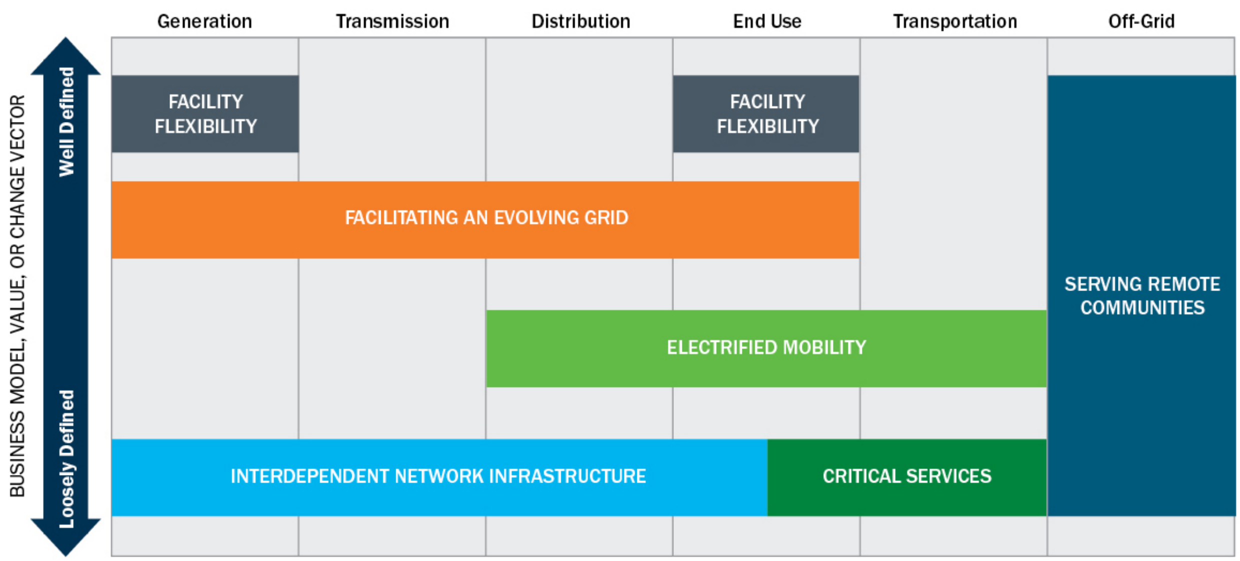

Figure 2. Illustration of the preliminary Use Cases

Activity 2: Building a Portfolio of Technologies

With these Use Cases defining a set of required functionality, the next step is to identify achievable and aggressive performance goals to thoroughly address the challenges presented in each Use Case. The proposed translation from Use Cases to specific energy storage technologies can be visualized through Figure 3.

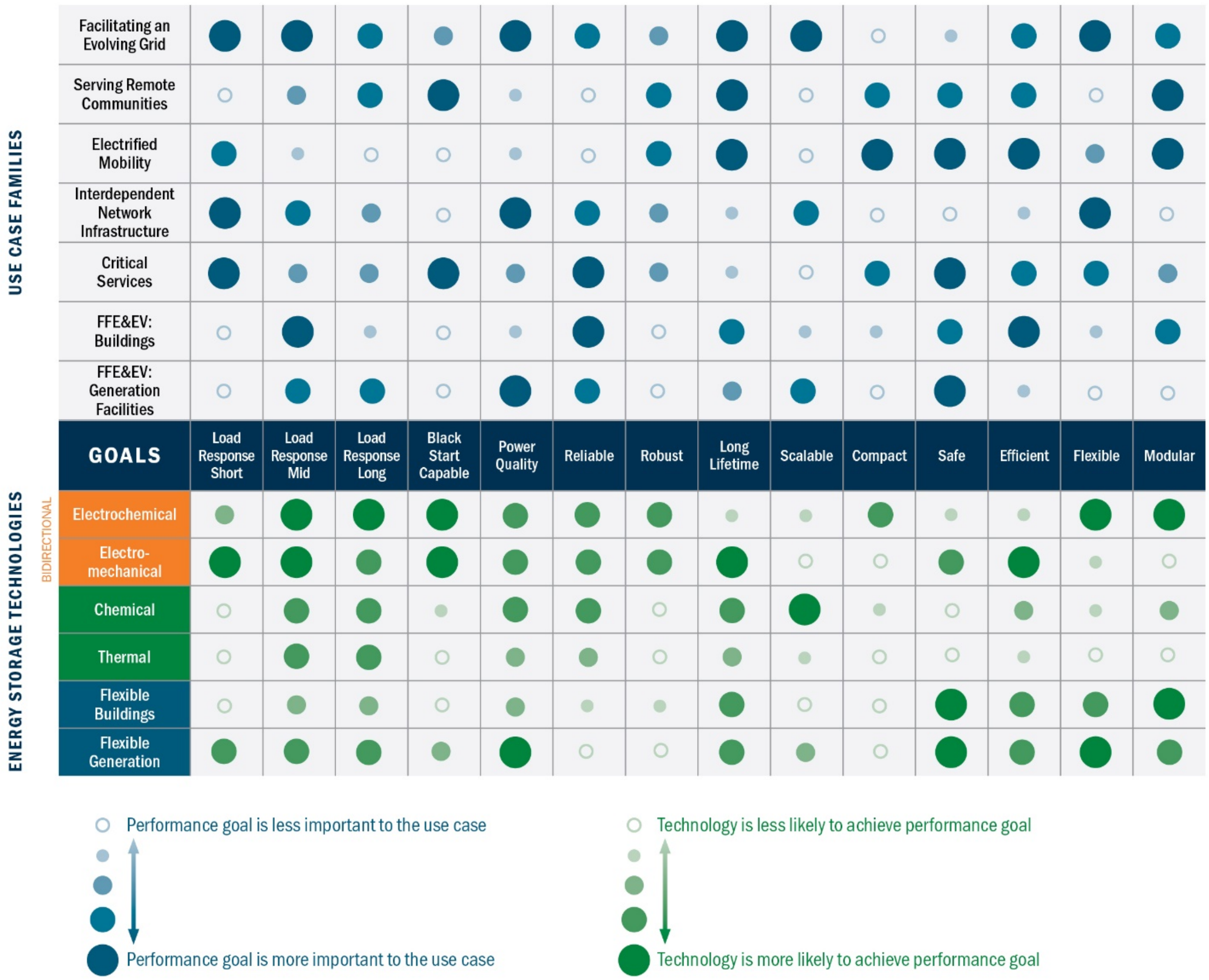

Figure 3. Example illustration of the performance functional framework

Performance goals are characteristics such as a system's lifetime, mobility, and efficiency, which would need to fulfill certain requirements as determined by the requirements and conditions in each Use Case. In Figure 3, all relationships comparing Use Cases to performance goals and Use Cases to technologies are displayed. The energy storage technologies listed in Figure 3 represent some high-level categories that align with Table 15 of Appendix 3 (for example, "Electrochemical" includes Li-ion, Na-Ion, Lead Acid, etc.), so the figure serves as a generalization for how well any particular technology meets a performance goal. Descriptions of the performance goals, along with other key terms in this Roadmap, can be found in Appendix 2.

The ESGC has identified initial performance goals relevant to each Use Case and more specific requirements for each goal. As the ESGC is implemented, specific technology development activities will be linked to these goals. Technologies that, with future R&D improvements, are capable of fulfilling a certain goal will form the high-level basis for potential technology pathways that will address Use Case requirements. Throughout the execution of the ESGC, the Use Cases, performance goals, and technology pathways will be periodically re-examined. To facilitate comparisons of technology costs with Use Case values, the ESGC is standardizing metrics across technologies that take into account the life cycle cost of storage, such as the Levelized Cost of Storage metric used in the ARPA-E DAYS program, and the use of common terms for energy storage components (see Figure 23 in Appendix 5).[23]

Technology Pathways Discussion. In examining technology pathways to meet the needs of the different Use Cases identified, the ESGC will take into account how commercial market forces will impact the adoption and availability of some technologies.

For example, the largest market for energy storage in the coming decade is electric vehicles (EVs). Therefore, the performance demands of the EV market are likely to have a major effect on the performance and availability of energy storage systems for other Use Cases in the near-term to mid-term. Significant EV-relevant advances in Li-ion technologies have occurred in the last decade, leading to a reduction in battery pack costs by ~85% over that time period.[24] These cost reductions, in turn, have been leveraged by stationary applications, with the majority of new grid-connected storage resources using lithium-based chemistries.

Using the Use Cases as a long-term guide, the present-day commonality between mobile and stationary storage technologies may diverge. With greater duration requirements and less stringent density or weight constraints, non-lithium storage technologies may emerge as the most cost-effective solutions for these new Use Cases. The combined efforts under the ESGC aim to determine the feasibility of such a potential future, and enable it to become a reality in the United States. As the ESGC strategy development continues, specific technology pathways can be mapped to one or more Use Cases. Each Use Case is envisioned to have multiple supporting technology pathways, and each technology pathway can contribute to multiple Use Cases. Appendix 3 also provides a summary table of current DOE activities across the spectrum of storage technologies.

Activity 3: Accelerate the Innovation Ecosystem

With an awareness of potential market outcomes, the ESGC has identified potential scopes for manufacturing capacity, commercialization efforts, demonstration projects, testing and validation facilities, and fundamental research. A hypothetical 2030 storage industry scenario envisions rapid R&D success in meeting performance and cost targets that achieve the “success statements” identified in each Use Case. Under various projections, the annual U.S. stationary energy market opportunity could grow from about $2 billion in 2020 to between $6 and $20 billion in 2030, allocated among a variety of firms and technologies.[25] These estimates include the various sub-markets typified by the Use Cases, as described by commenters in Table 2.

[23] https://arpa-e.energy.gov/sites/default/files/documents/files/DAYS_ProgramOverview_FINAL.pdf

[24] https://www.anl.gov/cse/batpac-model-software

[25] Based on and extrapolated from Wood Mackenzie, “U.S. Energy Storage Monitor Q4 2019,” December 2019; Bloomberg NEF, “2018 Long-Term Energy Storage Outlook,” November 2018; and UBS Research, “Energy storage: Are we at the tipping point,” November 2019.

Table 2: Selection of comments detailing market growth projections by Use Case

Use Case	Addressable Market Commentary
1. Facilitating an Evolving Grid	• "The global grid-scale battery storage market size was estimated at USD **2.6 billion** in 2019 and is expected to register a compound annual growth rate **(CAGR) of 24.4% from 2020 to 2027**."[26] • "ESA estimates that the deployment of **100 GW** of energy storage **by 2030** (ESA 100x30 vision) would create **at least 200,000 jobs**, without accounting for a surge in U.S. technology innovation or expansion of domestic manufacturing."[27] • "EIA forecasts renewable penetration to reach 38 percent and 17 GW of energy storage capacity will be added to the U.S. electric grid by 2050."[28]
2. Serving Remote Communities	• "Bloomberg NEF reports Global Microgrid expansion rate is **~50 projects/yr** with average rating of **20kW**. Growth expected to double by **2025;** Critical Services is much larger, with 200 projects per year at 500kW."[29]
3. Electrified Mobility	• "EEI and the Institute for Electric Innovation (IEI) released a report in 2018 forecasting 18.7 million electric vehicles on the road by 2030. To support that many EVs by 2030, **9.6 million charging ports will be needed**."[30]
4. Interdependent Network Infrastructure	• "There are about **125,000 telecom towers** in the US (source: Wireless Estimator, 07/2020) and **4.1M globally.** The majority of towers use lead acid batteries with an average life of three years. In the US alone, the addressable replacement market would be **over 40,000 batteries per annum or approximately $700M**."[31] • "Industrial and digital economy firms are losing about **$45.7 billion per year** due to power outages, with an additional **$6.7 billion** in costs … from power quality disturbances other than outages. The EPRI study concluded that the cost of power outages for all industry combined is an estimated **at $120 to $190 billion per year**."[32]
5. Critical Services	• "Bloomberg NEF reports Global Microgrid expansion rate is ~50 projects/yr with average rating of 20kW. Growth expected to double by **2025;** Critical Services is much larger, with **200 projects per year** at **500kW.**"[33]
6. Facility Flexibility, Efficiency, and Value Enhancement	• "Based on actual experience in New York City and Chicago, a rough rule-of-thumb would be that a 1 million square foot facility could contribute almost 1 MW of flexible load capacity. Energy reduction would generally be 20% of HVAC electric energy use."[34]

26 Brookhaven National Lab (BNL) RFI Response Citing Grid-scale Battery Storage Market Size, Share & Trends Analysis Report by Product (Lead Acid, Li-ion) by Application (Renewable Integration, Ancillary Services), by Region (APAC, North America), and Segment Forecasts, 2020 - 2027)

27 Energy Storage Association (ESA) RFI Response

28 Edison Electric Institute (EEI) RFI Response Citing Energy Information Administration (EIA) Data

29 AESTUS Energy Storage RFI Response

30 Edison Electric Institute (EEI) RFI Response

31 StorEn Technologies RFI Response Citing Wireless Estimator and Orbis Research Data

32 International District Energy Information (IDEA) RFI Response Citing EPRI's *The Cost of Power Disturbances to Industrial & Digital Economy Companies*

33 AESTUS Energy Storage RFI Response

34 QCoefficient RFI Response

The lack of field-validated operational experience is often cited as a major impediment to commercialization of new storage technologies. Confirming the commercial viability of these technologies by 2030 will require companies to test innovative technologies at commercially relevant scale and operating environment. In turn, the upstream R&D to arrive at these demos would have originated from a number of technology pathways, including the ESGC categories of Bidirectional Electrical Storage; Thermal and Chemical Storage; and Flexible Generation and Load. Figure 4 shows how firm size and demonstration-to-commercialization conversion ratios could translate into a sufficiently optimal portfolio of demonstration projects, applied development, and early stage research.

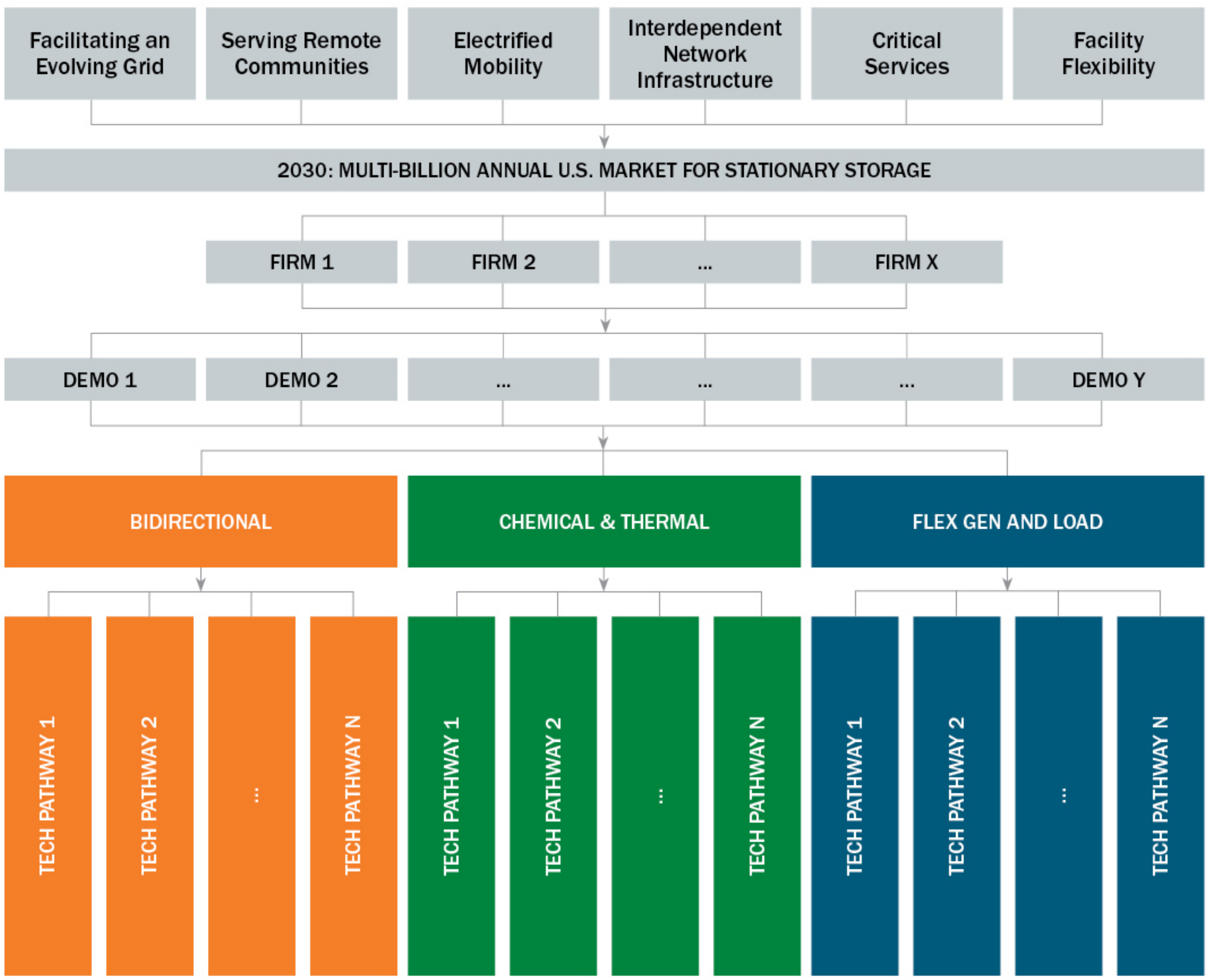

Figure 4. Illustration of a 2030 storage industry scenario

These companies and their associated demos would likely span a range of technologies including bidirectional electrical, thermal and chemical, and flexible generation and load. Each of the technology pathways identified in Appendix 3 could be accelerated through a network of DOE and industry activities, such as consortia, partnerships, and test facilities. Mapping the expertise and capabilities across the DOE/Lab complex will demonstrate the crosscutting ways in which these pathways can be utilized to achieve improved performance/metrics for energy storage systems that solve ambitious challenges. An example of what this mapping could look like for Electrochemical R&D led by the Office of Electricity is shown in Figure 5.

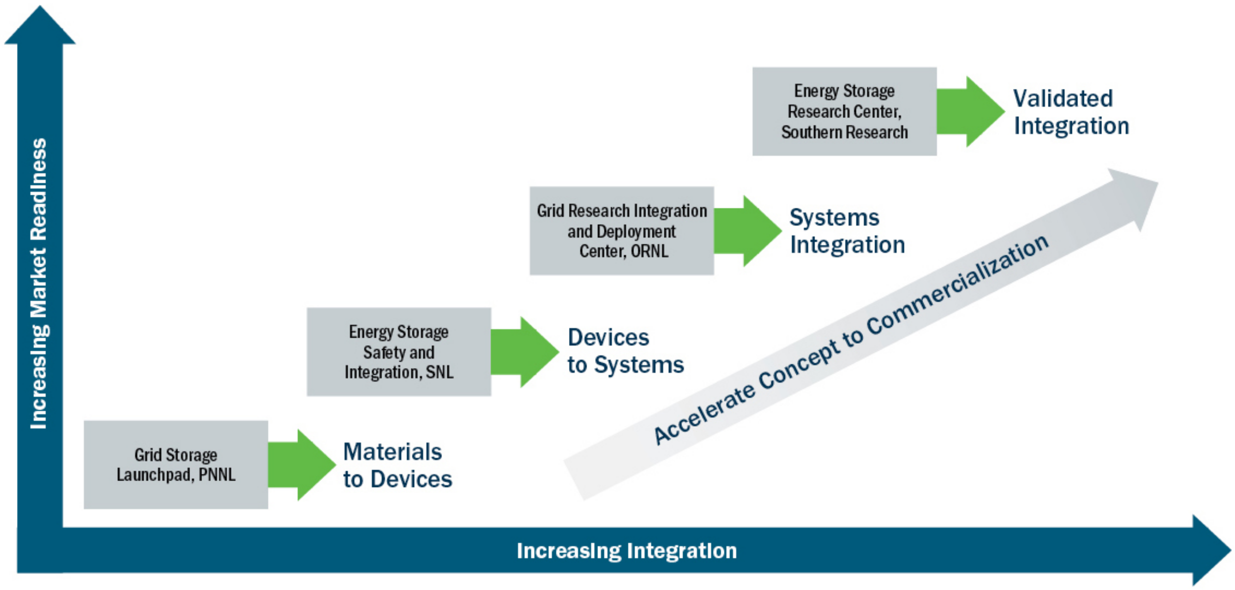

Figure 5. Example of a technology pathway for electrochemical storage

At the early stages of research, from foundational science to prototyping, DOE support will remain broad to support the unique requirements of many technologies. As each technology approaches market readiness, DOE support should become increasingly technology-neutral and geared towards the ultimate end user requirements (i.e., through the Use Cases).

Accelerate technology development in two areas:

1. New or augmented technology pathway infrastructure (especially development or test facilities) that enable rapid, early performance validation of storage and flexibility technology concepts.
2. Demonstration projects to enhance end user confidence and facilitate market adoption, which could be structured as integrated regional demonstrations that tie in technology, policy, manufacturing, and workforce, as discussed later in this document.

These efforts will be guided by the Use Cases and their functional requirements, which in turn will be revisited and updated periodically by the DOE RTIC. As shown in Figure 6, this process will incorporate information about technology cost and performance, as well as market and energy system scenarios, in order to help identify where the ESGC can target transformational activities in R&D and stakeholder assistance. Based on stakeholder feedback, DOE will complete an initial Use Case refresh in two years, with subsequent updates to be completed as required.

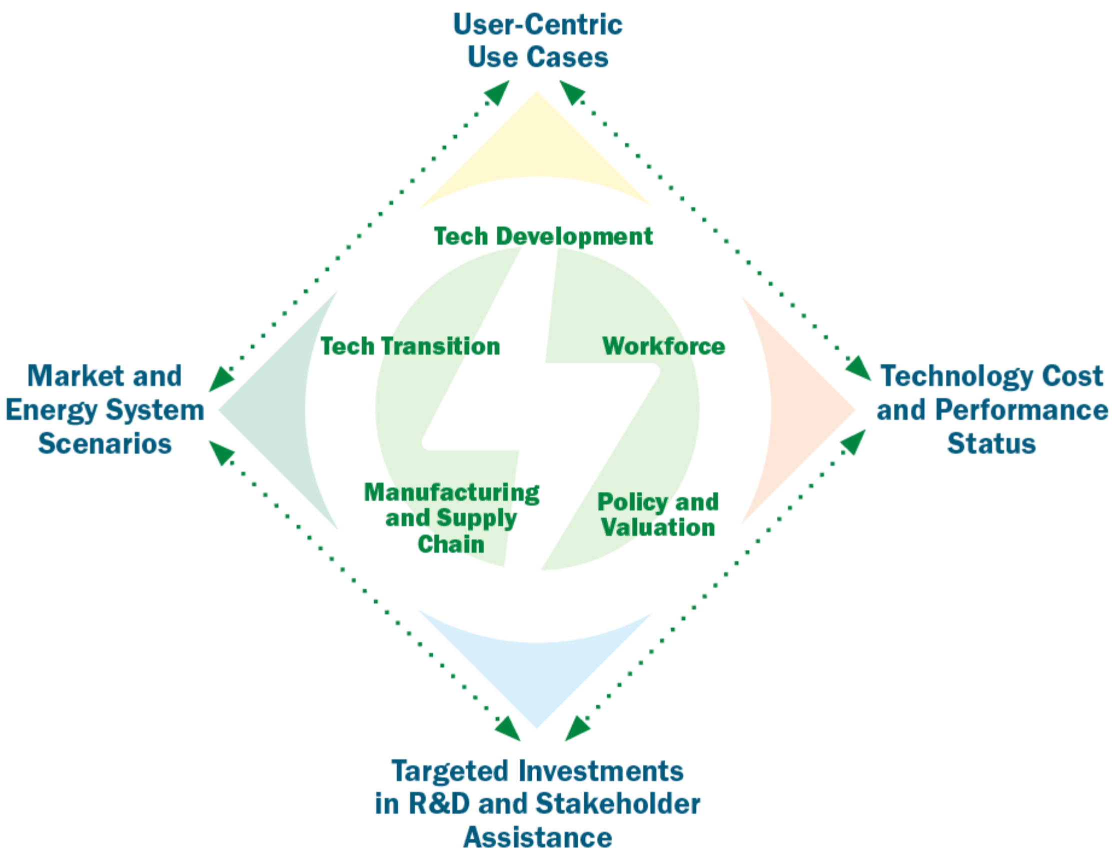

Figure 6. Interrelated ESGC Use Case and Goal Update Process

Measuring Success

Each Use Case includes price targets that may be ranges, recognizing that within any Use Case, values to the beneficiary can vary based on local market conditions, grid topology, climate, and a variety of other factors.[35] The Manufacturing and Supply Chain (M&SC) Track, detailed in the following section, will aim to bring manufacturing costs to meet or fall below these price targets. The ESGC focal targets highlight the two Use Cases with the largest potential markets—Facilitating and Evolving Grid for stationary applications, and Electrified Mobility for onboard vehicle applications. While each Use Case has specialized requirements and benefits, achieving the focal targets will also help achieve the cost and performance targets for all Use Cases.

[35] For cost ranges, the Version 1.0 Use Case goals will use the midpoint of the range, making the simplifying assumption that technologies at the midpoint price target will become a fully commercially viable solution to serve that Use Case, and include that price point as part of a suite of metrics to quantitatively measure progress.

These goals will be revisited periodically as detailed above. The refresh cycle is intended to account not only for advances in technology, but changes in market conditions, improved information about valuation, relevant policies, and requirements that can influence the value to the end user.

Facilitating an Evolving Grid	
Drivers • Increasing adoption of variable resources • Dynamic changes in customer demand	**Potential Price Target(s)** • \$0.03-\$0.05/kWh levelized cost of storage

Electrified Mobility	
Drivers • Lower EV battery manufacturing costs and improved performance • Distribution delivery capacity for fast charging	**Potential Price Target(s)** • \$80/kWh manufactured cost for battery pack • \$104/kw-yr storage capex

Critical Services	
Drivers • Disaster-related and other power outages	**Potential Price Target(s)** • \$77/kw-yr for reliability applications • \$1392/kw-yr for backup generator offset

Serving Remote Communities	
Drivers • Electricity premium due to fuel logistics and maintenance • Fuel supply disruptions	**Potential Price Target(s)** • \$65/mwh delivered energy

Interdependent Network Infrastructure	
Drivers • Grid interdependencies mean loss of function and service within these infrastructures can have far-reaching costs and impacts	**Potential Price Target(s)** • \$77/kw-yr storage capex

Facility Flexibility, Efficiency, and Value Enhancement	
Drivers • Enhance the overall facility value to the owner, operator, and the end consumer	**Potential Price Target(s)** • \$85/kwh, \$52/kw-yr for commercial and residential buildings • \$20-\$52/kw-yr for energy intensive facilities

Figure 7. Use Case and selected price targets or ranges

To achieve U.S. energy storage leadership, the Technology Development Track will continue to pursue activities that bring forward or accelerate the date at which storage becomes a commercially viable solution for all ESGC Use Cases. Each Use Case outlines an envisioned "addressable market." While a Use Case defines a distinct use for energy storage, the price at which storage becomes a viable option will vary depending on market conditions, availability of substitutable resources, and a variety of local factors. In this first iteration of Use Cases, the ESGC has selected price targets where storage becomes a fully commercially viable and cost-effective solution for the Use Case. These targets have been set at levels noted in various industrial literature as a significant marker of technology adoption.[36,37,38] See Appendix 3 for references and sources of potential price targets.

As DOE-supported R&D efforts continue to achieve cost reductions and performance improvements for individual technologies (e.g., thermal storage in buildings, long-duration flow batteries, pumped hydro,

36 Daniel J. Packey, "Market Penetration of New Energy Technologies," NREL/TP-462-4860, 1993.

37 Lund, Peter. "Market penetration rates of new energy technologies." Energy Policy 34.17 (2006): 3317-3326.

38 Balducci, P. J. "Plug-in hybrid electric vehicle market penetration scenarios." PNNL-17441 Report. Pacific Northwest National Laboratory. Richland, WA (2008).

etc.), integrated solutions appropriate to each Use Case begin to achieve cost parity for an increasing share of the market. Across all applications in all Use Cases, by 2030, the ESGC will seek to advance energy storage technologies that develop cost effective energy storage solutions for all Use Cases and accomplish the supply chain, workforce, and other criteria as outlined later in this Roadmap.

Manufacturing and Supply Chain

Track Overview

Purpose: Build and diversify a strong domestic manufacturing base with integrated supply chains to support U.S. energy storage leadership.

Need: To fully capture the benefits of energy storage technologies, the U.S. will need a robust manufacturing enterprise that can drive costs down, rapidly integrate and scale production of innovations, and reliably source critical materials and components. To become a world leader in energy storage, the United States will need to achieve the goal of “Make Here.”

Mission: The Manufacturing and Supply Chain (M&SC) Track of the ESGC will identify and address major challenges to lowering manufacturing costs as well as barriers to improving the performance of storage systems.[39] Learning from recent major DOE initiatives, the ESGC will include domestic manufacturing presence as a major goal, which requires developing a robust, multi-faceted strategy.[40] The Track will identify and pursue opportunities to accelerate scale up of manufacturing innovations from the laboratory bench to demonstration to commercialization. The Track will also pursue process innovations that enable reliable sourcing of critical materials and components across supply chains. Finally, this Track will develop a coordinated strategy that prioritizes and integrates investments.

What is the role of the government? What is DOE’s role? DOE plays a critical role in accelerating progress by supporting work that helps to overcome the many barriers that may arise along the trajectory from discovery to manufacturing. DOE R&D advances materials and components used for multiple energy storage technologies and applications, as well as platform technologies that enable the manufacturing of energy storage systems. DOE also establishes partnerships to promote technology innovation and transfer knowledge through dissemination of tools and training.

The M&SC Track of the ESGC aims to be a force multiplier for the impacts of the Technology Development Track, tackling manufacturing and supply chain challenges in ways that bring technology advancements to scaled production and industry adoption faster.

Addressing Key Challenges through Manufacturing and Supply Chains

Make Here: The M&SC Track will focus on addressing the following challenges facing domestic production and supply chains of storage technologies:

- Scaling up and integrating emerging technologies from lab, to prototype, to commercialization
- Lowering the domestic manufacturing cost for storage technologies
- Improving performance while reducing the energy impact and life cycle cost of new technologies

39 This track focuses on the manufacturing of energy storage materials, components, and systems. Challenges related to generation and load flexibility within manufacturing facilities are addressed in the Technology Development Track section.

40 SunShot is a well-known, recent DOE effort to rapidly transform a clean energy industry. SunShot was very successful in its primary goal—i.e., to lower the cost of solar photovoltaics (PV). However, it did not include a strong domestic manufacturing strategy and the innovations did not ultimately translate into a major PV manufacturing presence in the United States.

- Strengthening domestic supply chains (including those in partnership with our allies and partners) by increasing domestic production across supply chain stages and minimizing dependence on foreign sources of materials and components.

Other challenges include issues related to capital costs of new factories and the difficulties for manufacturers to develop a business plan with the uncertainty of energy storage markets.

Table 3. Manufacturing challenges across storage technologies

Storage Type	Advance processing and recycling to diversify critical materials sourcing	Lower manufacturing cost			Improve performance (e.g., safety, life cycle cost)				Accelerate manufacturing scale up/scale out	Standardize systems design and testing protocols to streamline integration of innovations
		Membranes	Advanced anode, cathode, electrolyte, and chemistries	Containment structures and materials	Electrolyzers	Advanced storage materials	Bipolar plates	Heat exchangers		
Lithium-based Batteries	■		■					■	■	
Other Battery Chemistries	■	■	■			■			■	■
Flow Batteries	■	■	■	■			■		■	■
Mechanical Energy Storage						■			■	■
Chemical Energy Storage	■	■	■		■	■	■		■	
Thermal Energy Storage				■		■		■	■	■

Different energy storage technologies face a range of challenges including improving manufacturability and strengthening their supply chains (see Table 3). This section summarizes these technical challenges, which are grouped by different classes of energy storage technologies. Given the range of different chemistries and operational designs of various electrochemical storage technologies, electrochemical storage is divided into three separate subsections focusing on Li-based batteries, other battery chemistries, and flow batteries. Some challenges, shared by all technology classes, are described in a crosscutting section.

Electrochemical

One major challenge preventing the creation of more battery manufacturers is that different battery chemistries usually require different manufacturing processes. A flexible manufacturing line capable of making battery components and cells of many different battery chemistries would enable a much more robust business case for manufacturers, allowing them to supply a wider range of customers. At the other end of the supply chain, electrochemical battery recycling provides an opportunity to recover valuable materials, yet current challenges in waste treatment, disposal costs, and water consumption prevail.

Li-based Batteries

The demand for lithium is correspondingly large and growing. The following list details the three-pronged challenge in developing Li-based batteries.

1. **Limited supply chain**. The United States currently does not produce lithium from its reserves and imports lithium from other countries, creating a supply chain risk. The most common type of Li-based battery today—the Li-ion battery—also requires cobalt. The United States does not have large reserves for cobalt, so the most viable pathway for a domestic supply chain is through battery recycling.

2. **Battery manufacturing processes challenges limit cell performance at market competitive cost**. Technical challenges in manufacturing processes currently limit energy density and battery lifetime. While there is an unavoidable tradeoff between energy density and power in battery technologies, new approaches to component design, cell architecture, and manufacturing processes could improve cell performance at reduced life cycle cost. In addition, there is an opportunity to leverage existing high-throughput, low-cost manufacturing processes in adjacent areas for the energy storage arena (e.g., retooling commercial and scalable manufacturing of photovoltaic thin film for silicon anodes).

3. **Technical challenges to address safety issues**. Li-ion batteries have been known to overheat, catch fire, and even explode under certain conditions. To ensure safety in all applications, better thermal management, including integration of improved heat exchange and transfer technologies, needs to be integrated into the manufacture of battery systems. Alternatively, solid-state Li-based batteries—which can involve powders and densified layers—have reduced thermal management issues. Manufacturing research can help to determine the most economical and safest approach, especially since safety requirements affect the overall system's manufacturing cost.

In addition to investments in architectures and processes, innovation in the design of specific battery components can also increase performance without the incorporation of new materials, allowing readily manufacturable "drop-in" improvements in technologies. Significant opportunity remains to optimize battery components, such as the anodes, cathodes, separators, and electrolyte, and further work can develop and test materials and cell performance.

Incorporation of advanced materials into battery components is another way to improve their performance, lower their cost, or both. For example, ongoing work is aiming to develop less expensive materials for cathodes with better capacity. Continued work can improve their manufacturability, such as enhancing the uniformity of coatings, so they can be optimized and integrated without a massive battery redesign.

Finally, much remains to be done to take full advantage of our core expertise and develop U.S. manufacturing leadership in the lithium-based battery space. The United States has a strong R&D community, led by universities and National Labs, a strong innovation infrastructure for technological advancement of batteries, and an emerging Li-ion battery manufacturing industry. However, this world-leading R&D base has not yet translated into a domestic supply of materials and equipment that can be sustained in the event of supply chain disruptions.

Flow Batteries

Flow batteries have been designed with different Use Cases in mind from other electrochemical storage. While the incumbent Li-ion battery chemistry is presently the most cost effective for shorter durations—those less than 4-6 hours—the projected market for flow cells, in which the power (kW) of the battery is decoupled from the storage capacity (kWh), is quickly growing. In addition to high electrolyte cost attributed to raw materials (i.e., vanadium), other challenges to developing flow batteries are described below.

1. **Inefficient and expensive manufacturing technologies**. Components such as membranes, bipolar plates, and porous carbon electrodes require specialized properties and are currently expensive to produce. Auxiliary components such as pumps are also expensive to produce.

2. **Lack of robust, standardized supply chains (limited suppliers) and system integration challenges**. Similar to other battery chemistries, the potential of flow battery systems is limited by non-standardized supply chains, which reduce the interoperability of individual manufacturing innovations that fit within a larger flow cell system. The current most common flow battery chemistry relies on vanadium, a material that is mainly imported. Therefore, supply chain constraints would inhibit market penetration if the demand for this chemistry grows.

3. **Challenges with manufacturing scale-up**. Flow batteries have not yet achieved manufacturability levels that support deployment sufficient to provide broad economies of scale. Near-term advances for flow systems are focused on achieving comparable technical performance relative to incumbent Li-ion batteries; however, once systems are further developed and commercialized, scaling up manufacturing processes for specialized high performance components (such as membranes and storage tanks) and materials (such as the active electrolyte) will be extremely critical.

Other Battery Chemistries

The cost, safety, and other requirements for stationary storage have led to the reexamination of batteries based on other chemistries that do not have the same critical material requirements or inherent safety risks as Li-ion batteries. For example, various Na-ion battery designs may have some cost advantages over Li-ion batteries, but only if they do not contain cobalt or other expensive, critical elements. With such a strong market demand for Li-ion batteries in recent years, innovations that would make these alternative battery chemistries competitive still face barriers to manufacturing scale-up and design to enable seamless integration into today's infrastructure.

For example, next-generation sodium-sulfur (Na-S) batteries would benefit from breakthroughs in sodium-ion conducting membranes (e.g., sodium Super Ionic CONductor (NASICON)) that include reduced thickness (~25 microns) and sustain mechanical robustness when cycling at temperatures up to 60°C. Manufacturing advancements could also reliably produce large area single membranes (400 cm^2) while minimizing defects that degrade performance.

In addition, there has been a revolution in improving the recyclability of some of the older rechargeable batteries, such as advanced lead-acid (PbA) batteries and batteries that use zinc. However, new and yet to be identified methods could simplify battery chemistry separations at recycling stations to prevent contamination in material recovery.

There are still other non-Li-based (excluding flow batteries) battery chemistries that are in much earlier stages of technology development that use earth-abundant materials and have the potential to improve safety. At this time, the major challenges concern achieving performance characteristics that are competitive with Li-based chemistries and other energy storage technologies. Farther in the future, however, once these battery chemistries realize energy densities, reliability, and lifetimes competitive with Li-based batteries, they will face many of the same manufacturing challenges that Li-based batteries face now, as described above.

Mechanical Energy Storage

Efforts in improving mechanical energy storage systems, such as pumped water, compressed air, and spinning flywheels, aim to lower the cost of producing and developing systems, as well as widen the range of situations and environments in which they are useful and cost effective. While most mechanical energy storage systems utilize well established materials and technologies, there is a need for innovation to make these systems more robust and able to respond to the challenge of a grid with increasingly variable supply and demand. In the past, mechanical storage systems have been designed to support base load operation, but in the future, more resilient systems may include more sophisticated power electronics controls. The following list describes the challenges to improving mechanical energy storage.

1. **High cost of manufacturing**. In order to enable mechanical energy storage to compete with other storage technologies for grid applications, future R&D efforts should focus on improving the modularity and lowering the cost of manufacturing and building the systems. Related manufacturing challenges include lowering the cost of manufacturing and improving the manufacturability of existing components as well as new components with advanced materials to increase performance and system lifetime. For example, in pumped hydro applications, advanced materials could be used in higher strength turbines capable of enduring greater operational strains due to switching rapidly from part to full load conditions and supporting advanced applications where missing just a part of a cycle can be detrimental to operations.

2. **Safety constraints**. Mechanical energy storage R&D has some unique safety constraints. For example, labs testing compressed air systems generally require concrete or other construction capable of sustaining an overpressure condition. Flywheels, which can be massive, also require such precautions in case of a component failure during testing when containment of the movement of such components is needed. Such labs also generally require remote data and remote cameras, and such precautions are likely to be required in real-world applications. Parameters of particular interest to mechanical energy storage systems include component and system-level performance efficiency and reliability, life cycle reliability, and materials strength, as well as model validation and demonstration of safety technologies.

Chemical Energy Storage

A major challenge for currently utilized chemical energy storage systems is cost competitiveness with other energy storage media. For chemical storage to be competitive with other storage technologies, cost reductions are needed both in the synthesis of hydrogen (e.g., compressed gaseous H_2 or cryogenic liquid H_2) or other hydrogen-rich carriers such as ammonia or methanol, and in the chemical storage components.[41] The technical barriers to achieving more widely adopted chemical energy storage are discussed below.

1. **Manufacturing cost**. Manufacturing innovations can reduce cost in various storage vessel configurations (e.g., carbon-reinforced metal tanks). More importantly, major advancements can be made in reducing costs by developing lower cost manufacturing methods for electrolyzers used in chemical-carrier synthesis. Manufacturing costs in electrolyzers can be reduced in part with projected cost reductions resulting from economy-of-scale production at levels of many thousands of stacks annually, well beyond current levels. Emerging manufacturing technologies, such as roll-to-roll manufacturing, additive manufacturing, and increased automation of the cell and stack assembly processes, currently at the R&D stage, have the potential to enable the higher production volumes needed.
2. **Dependence on critical materials**. Some electrolyzer components require materials that are not domestically sourced, creating supply chain risk points, commonly characterized as critical materials challenges. For example, platinum- and iridium-based catalysts are platinum group metals with low abundance that are obtained mainly from regions outside the United States, which could create critical supply chain issues if manufacturing volumes ramp up. There are opportunities to decrease reliance on these materials through technological advances that decrease the amount of material required or to develop replacement materials. There may also be opportunities for the United States to find ways to domestically source these critical materials, through improved recovery from obsolete parts and the creation and discovery of new domestic raw material sources.
3. **Performance of components in acidic environments**. The acidic environment of polymer electrolyte membrane electrolyzers presents another challenge. Specifically, the acidic environment of these systems requires corrosion resistant materials, such as platinum and iridium oxide catalysts, as well as bipolar plates, typically made of titanium, which all increase the cost. Manufacturing methods and materials currently used for producing the bipolar plates are also expensive, since the coating processes used to prevent corrosion require batch processing after stamping. Advanced manufacturing methods for manufacturing the anode and cathode catalysts layers have potential for improving performance and reducing cost.

Thermal Energy Storage

Thermal energy storage (TES) has the advantage of inherently decoupling capacity (in a thermal reservoir that typically has a low marginal cost to increase in size/duration) and power (via a heat exchanger that delivers energy to a heat engine or other application). TES systems allow heat to be

[41] Chemical storage components are the parts that store chemicals, either stationary or for transport, such as tanks. Components associated with more technologically mature carriers (e.g., natural gas) are not included here.

stored and recovered using three potential approaches: (a) sensible heat, (b) latent heat (phase change), and (c) thermochemical heat. Each of these three approaches has their own unique barriers to improved performance and lower manufacturing costs and can be further divided into high-temperature applications (primarily for electricity generation) or low-temperature applications (primarily for residential or commercial building or industrial process loads). Although thermochemical technologies attract much interest due to the high energy density that can be stored in chemical bonds, thereby potentially shrinking the footprint and capital costs of TES systems, the approaches with the most likely near-term impact involve sensible and latent heat.

1. **Manufacturing cost**. While thermal energy storage, in one form or another, is one of the oldest energy storage technologies that has been harnessed, there are numerous new technology development pathways to improve its utility. In particular, for electricity generation, going to higher temperatures (>700°C) will allow TES to store and deliver heat to high-efficiency, next-generation power cycles, like those that use supercritical carbon dioxide (sCO_2) as a working fluid. Before such technologies can become widespread, the manufacturing cost of advanced materials and components that can withstand these harsh environments must be lowered, particularly focusing on containment materials to hold and transport storage and heat transfer media. Innovations in high-strength alloys based on nickel or cobalt, in appropriate forms, could reduce the current high cost of systems constructed from those materials. A primary challenge is developing supply chains that currently have low levels of competition in order to reduce the material costs of alloys, improve the manufacturing of components (e.g., casting high nickel alloys, forging or casting valves, making seamless or cast pipe, and heat exchanger manufacturing), and/or enable the wider use of low-cost ceramic materials.
2. **Manufacturing processes**. In addition to lowering cost, high-temperature thermal storage also requires the development of manufacturing processes to improve resistance of components to corrosion and erosion, which is typically exacerbated at higher temperatures. Coatings and claddings can potentially be developed for high resistance to operational conditions, but new methods for in situ reapplication and maintenance, particularly for high-surface areas and narrow diameter tubes and pipes, could address this barrier.

Crosscutting Challenges

The challenges described thus far have mainly been specific to one or two energy storage technology families. Yet, other manufacturing and supply chain challenges shared by most or all technologies do exist, which are presented below.

1. **Insufficient system integration capabilities**. All energy storage technologies will need to be integrated into larger systems, such as buildings, microgrids, distribution networks, or regional electric grids. Especially in the case of bidirectional storage technologies, fine control of electricity flow will be needed for seamless transfer of power (e.g., matching voltage, phase, and avoiding higher order resonance problems). This requires the development and standardization of power electronics and other support technologies, such as supercapacitors, tailored to fit the wide range of situations where energy storage will be integrated into a larger system, facility, and grid operations. The United States currently has some production capability for power electronics; yet, there is ample opportunity to scale up design, production, and testing capabilities.

2. **System design and test capabilities**. Rapid development of new materials and components cannot be incorporated into systems without the ability to design and test those changes, as well as develop manufacturing flows to scale production of new systems. Improving system design and test capabilities for all energy storage technologies can greatly accelerate the commercialization of viable innovations.

In order to stay ahead of the challenges and opportunities that emerge as industries overcome those described here, continued work should focus on improving and updating our understanding of manufacturing challenges and opportunities (e.g., automation to reduce battery cost or low temperature, cost-efficient, and sustainable methods). Regular communication between researchers and industry representatives on manufacturing challenges and the scientific understanding of manufacturing processes can help maintain the process of continual improvement.

Impact

The R&D process of innovation is not linear, nor is it limited to a lab. As illustrated in Figure 8, low technology readiness level challenges exist at all manufacturing scales. Regardless of scale, it is necessary to prove the performance, reliability, and cost of innovations to reduce uncertainty and risk of market failure.

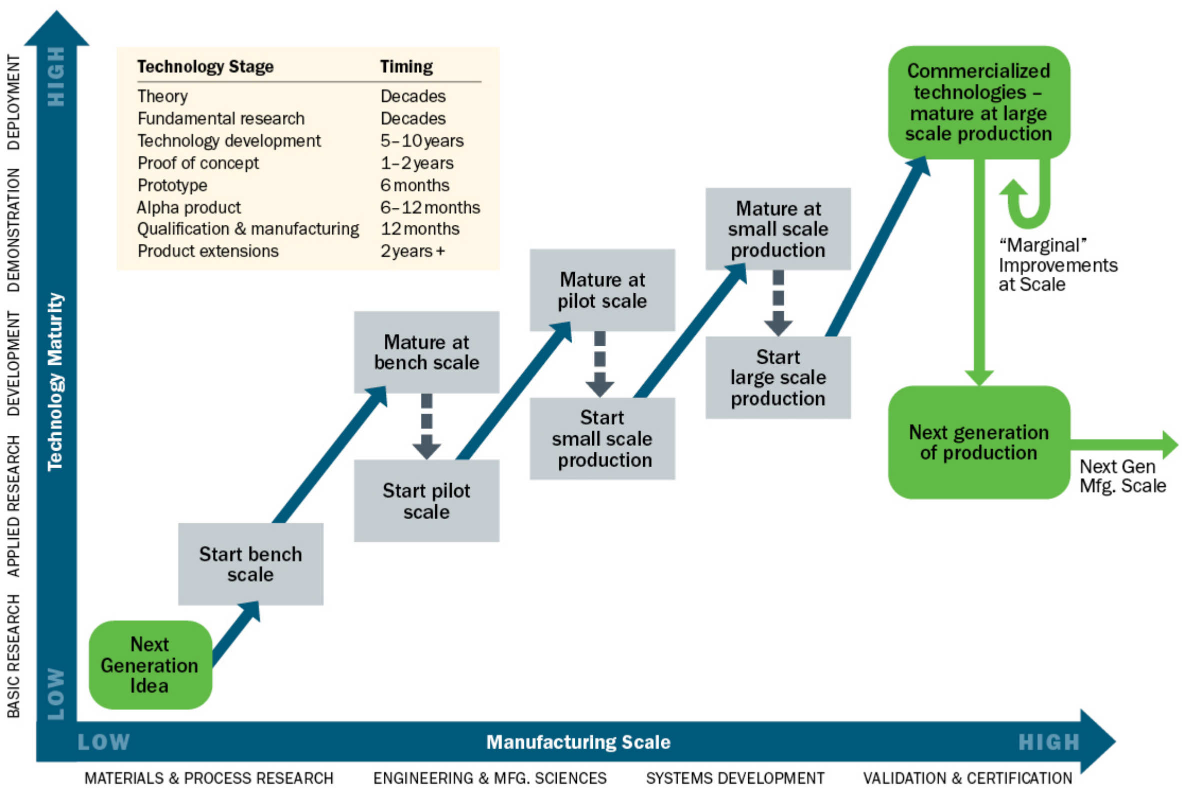

Figure 8. Technology maturity and manufacturing scale pathways

In today's competitive global economy, many countries recognize the importance of establishing leadership in the foundational industries of tomorrow, which involves being the first to translate scientific innovations into new manufactured products available on the global market. One of our nation's greatest strengths is the ability to innovate. Across National Labs, universities, start-ups and large corporations, knowledge and creativity are harnessed to produce and support new ideas to improve existing technologies or create new ones. Energy storage is an industry space with tremendous opportunity for innovation to expand its capabilities and adoption across the globe. With today's competitive global industries, the United States can maintain its lead by out-innovating competitors. The M&SC Track is focused on key activities that can translate successes in the lab into competitive advantages for U.S. industries.

Activities

Individual offices within EERE, as well as FE, NE, and ARPA-E, have funded and continue to fund R&D that both directly and indirectly addresses manufacturing and supply chain challenges. With the ESGC, these offices have increased coordination to build a shared understanding of 1) the full range of manufacturing and supply chain challenges across energy storage technologies, 2) how their individual efforts address these challenges, and 3) where opportunities lie to more comprehensively and directly address them.

Five major goals have been identified for addressing manufacturing and supply chain challenges. The ESGC will leverage existing efforts by DOE offices to ensure "make here" becomes a reality. Additional details on specific office activities are included in Appendix 3. The major manufacturing and supply-chain goals are:

1. **Develop a deep understanding of technical barriers in production and manufacturing for a wide range of energy storage technologies, identifying key technical metrics**. As energy storage technologies and markets evolve, DOE will continue to work with original equipment manufacturers (OEMs) and other stakeholders to examine key manufacturing bottlenecks for energy storage technology systems. To increase the understanding of shared technical barriers in production and manufacturing, multiple DOE offices will conduct targeted technical analyses and workshops on existing industries and the barriers they face. For example, the Advanced Manufacturing Office (AMO) and Vehicle Technologies Office (VTO) within EERE will conduct assessment studies for energy storage and related technologies. The ESGC will build on the findings of these studies to guide its efforts in the other manufacturing and supply chain activities described below and conduct additional studies in the future, as deemed necessary.

2. **Support innovations to lower manufacturing cost and overcome technical barriers**. The ESGC will prioritize materials and manufacturing R&D investment informed by the technical analyses above. Multiple DOE offices have ongoing and planned R&D investments with industry performers to address the challenges identified earlier in this section. Some of these efforts are directly focused on improving energy storage systems, often led by offices with missions that directly involve energy storage. For example, ongoing efforts include lowering the manufacturing and life cycle cost of cathodes in Li-based batteries and improving the manufacturability of components that operate in the high temperatures of some advanced thermal energy storage systems.

   While other R&D programs are not directly focused on energy storage, they are developing manufacturing-oriented solutions that could apply to energy storage systems, such as AMO projects improving the manufacturability of materials for harsh service conditions.

Moving forward, the ESGC will serve as an information-sharing commons for DOE offices to share progress on their manufacturing and supply chain-related investments and identify opportunities for coordination, collaboration, and new activities. The M&SC Track of the ESGC will complement the innovations that bring new energy storage technologies with innovations that lower cost and increase the ability to rapidly scale up their production.

3. **Facilitate scale-up of emerging manufacturing processes through partnerships with industry and ensure U.S. capabilities for testing/validating manufacturing innovations meet stakeholder needs**. Scaling from a lab prototype to the pilot scale and beyond is time consuming and expensive, sometimes taking as much as a decade. Addressing this issue through collaborative work to validate and scale new manufacturing processes with proper intellectual property (IP) protections could help to accelerate deployment of next-generation technologies, resulting in U.S. manufacturing leadership in emerging energy storage technologies. The ESGC will coordinate efforts to validate and scale up components and production processes related to various energy storage technologies.

   In some cases, DOE's R&D investments are paired with efforts to speed the scale-up of solutions that are developed. For example, programs developing and improving the manufacturability of new thermal energy storage technologies are also innovating new thermal energy storage system designs to accelerate their commercialization. Also, efforts are underway to scale up manufacturing processes for electrolyzers, both for size of parts and volumes.

   Offices participating in the ESGC also fund activities focused primarily on accelerating innovations through the process of field validation and manufacturing scale-up, such as prototyping and field-validating scale-up efforts in new Li-based battery manufacturing processes, while ongoing OE projects focus on validating the reliability and safety of grid-scale energy storage systems to facilitate ubiquitous acceptance.

   Under the ESGC, these scale-up activities will continue. In addition, the M&SC Track, in collaboration with the Technology Transition Track, will explore additional opportunities focused on connecting innovative researchers and companies with public and private sector investor entities to accelerate their validation and manufacturing scale-up in ways that will foster a robust domestic supply chain for future energy storage technologies.

4. **Standardize systems design and testing protocols to streamline integration of manufacturing innovations for emerging storage technologies**. Integrating individual components from multiple manufacturers into emerging storage technologies and systems is challenging if standards and integration mechanisms are not in place. For example, manufacturers cannot design and produce a flow battery system for a particular application if they cannot calculate whether a certain combination of chemistry, architecture, and scale will fit their needs or achieve a sufficient return on investment. At the same time, researchers developing new materials and/or components for flow-batteries have the data—or the ability to generate the data—necessary to make those estimates, but no way to simply and easily make those

calculations and communicate them to industry in a widely accessible way.

DOE will work to streamline integration for emerging technologies such as flow batteries through supporting a combination of manufacturing R&D collaboration and analytical tools that bridge between individual component and integrated systems design and manufacture. Through this work, the storage technology systems manufacturers can better access a broader array of options for components and materials, while the manufacturers of individual components can better calibrate their own cost and performance targets. In addition, the performance and cost requirements of final system customers can be more effectively communicated throughout the ecosystem of manufacturers.

5. **Deepen understanding and pursue innovation to improve critical materials supply chain resilience, and advance processing and separations to diversify critical materials sourcing and improve recycling**. The growing storage sector has increased demand for critical materials such as cobalt, lithium, platinum group metals, and naturally-occurring graphite. The extraction and early stage processing of these materials are concentrated in a small number of countries outside the United States. For a number of years, DOE has been actively engaged in identifying and supporting the development of solutions to reduce supply risk and increase supply chain resilience by domestically sourcing these critical materials and reducing mainstream technologies' dependence on them. For example, AMO has funded the Critical Materials Institute, a public-private consortium addressing material criticality through supply diversification, substitutes, and recycling. In addition, over the past several years, VTO and AMO have supported battery recycling through the ReCell Battery Recycling Center and the Battery Recycling Prize.

   As part of the ESGC Roadmap, DOE will further refine a comprehensive approach to ensure that supply chain risks are understood and addressed in an integrated fashion. Particular focus will be made on scaling up innovative processing and separations of critical materials, including those recovered from unconventional sources, such as brines or mine tailings. In addition, DOE will maintain a strong focus on battery recycling R&D, amplifying and strengthening this work through the Federal Strategy on Critical Minerals.

6. **Establish a domestic battery manufacturing ecosystem**. In response to the identified opportunity for leveraging National Lab and research infrastructure resources, the Department will coordinate with other federal agencies to form a Federal Consortium for Advanced Batteries (FCAB).[42] The vision for this interagency group is to foster executive-level strategic alignment, coordination, and collaboration across the federal agencies to establish a domestic battery materials and technology supply chain that serves commercial and military applications. FCAB will accelerate the development of a robust, secure, domestic industrial base for advanced batteries by developing and supporting the implementation of an integrated strategy, providing as-needed analytics, and sharing best practices and information from energy storage-focused federal and industry working groups. FCAB will also support key U.S. Government policy initiatives to protect, enhance, and grow domestic development and production of lithium

[42] More information on the FCAB can be found at https://www.energy.gov/eere/articles/energy-department-and-other-federal-agencies-federal-consortium-advanced.

battery technologies. FCAB's long-term goal is to establish a domestic battery ecosystem in which small and large companies can thrive.

Measuring Success

The M&SC Track will measure the success of its efforts from a number of different perspectives, summarized in Table 4.

Table 4. Perspectives, goals, and metrics

Perspective	Goal	Metrics
Technology	Maturation of new technologies	Manufacturing Readiness Level (MRL)
Cost	Lower manufacturing costs to meet price targets	$/kW, $/kWh, LCOS, etc.
Production	Meet global demand (i.e., U.S. production capacity and production output)	MW/month
U.S. Supply Chain	Strengthen U.S. supply chain	% of U.S. presence in energy storage supply chain ecosystems

From a technical perspective, DOE will track the development of individual innovations through the established Manufacturing Readiness Levels (MRLs). The MRL provides a high-level, technology agnostic way to track the progress of the manufacturability of technical innovations from the experimental proof-of-concept stage—the ability to make one, to the industry standard stage—the ability to reliably and cost-competitively make enough to meet market demand (usually in the thousands or millions per year). As individual ESGC activities demonstrate advancement of technologies to higher MRLs, they become closer to commercial readiness.

The M&SC Track will also measure the impact of its efforts via component, system, and levelized cost metrics, examples of which are shown in Table 4. Significant time and resources are required to develop new technologies, but the impact that those technologies can have on the public welfare relies heavily on the scale and efficiency with which they can be produced. Concepts like "economies of scale" and "Wright's law" express different aspects of the fundamental relationship of unit cost and manufacturing volume capability of any technology.

Technical routes to achieve this cost reduction range from lowering material cost through separation innovation, to developing high-volume manufacturing processes that lower unit-cost, to developing more efficient manufacturing methods, and beyond. The ESGC plans to reduce manufacturing costs to meet the price targets across Use Cases, determined by the Technology Development Track, by 2030.

Finally, the M&SC Track will continually examine the relationship between its activities and the condition of global industries. Achieving the ESGC's ultimate goal involves improving the United States' standing relative to global competition. The ESGC will monitor the opportunity space to contribute to this impact using industry metrics, such as the U.S. percentage of global market share in energy storage industries, U.S. production capacity and production output (in MW/month), and U.S. supply chain strength, as a percentage of U.S. presence in energy storage supply chain ecosystems. The ESGC will monitor domestic production across the supply chain, including raw and refined materials and components necessary for energy storage systems. Detailed definitions of these industry-focused metrics can be found in Appendix 5.

Initially, the M&SC Track is focusing its cost reduction efforts on Use Case 1: Facilitating an Evolving Grid and Use Case 3: Electrified Mobility, as shown in Table 5. The system cost target for Use Case 1 translates to the levelized cost of storage target given in the Technology Development Track's section through scaling by cycle life. The battery pack cost target for Use Case 3 is the manufactured cost for a battery pack for a 300-mile range electric vehicle. Over time, the M&SC Track will develop additional cost targets.

Table 5. Initial 2030 manufacturing cost targets

Use Case	Application or Technology	Baseline	2030 Cost Target
1: Facilitating an Evolving Grid	Flow batteries	$360/kWh[43]	$200/kWh system cost
3: Electrified Mobility	Vehicle batteries	$143/kWh[44]	$80/kWh battery pack cost[45]

43 2020 Grid Energy Storage Technology Cost and Performance Assessment (DOE/PA-0204), Kendall Mongird, Vilayanur Viswanathan, Jan Alam, Charlie Vartanian, and Vincent Sprenkle, Pacific Northwest National Laboratory; and Richard Baxter, Mustang Prairie Energy.

44 Rated battery pack cost from https://www.anl.gov/cse/batpac-model-software

45 https://www.energy.gov/sites/prod/files/2020/08/f77/Boyd-2020_AMR_Plenary-Batteries_and_Electrification_Overview_0.pdf

Technology Transition

Track Overview

Purpose: Strengthen U.S. leadership in energy storage through the commercialization and deployment of energy storage innovations.

Need: To develop standards, validate data, and prove business models that gives market participants confidence that an energy storage asset will perform to expectations and have market demand, thus reducing production or project risk, lowering project costs, increasing investment, and accelerating scalable deployment.

Mission: To realize the vision of U.S. energy storage leadership, the Technology Transition Track accelerates the technology pipeline from research to system design to private sector adoption.

What is the role of the government? What is DOE's role? The federal government seeks to improve the transition of federally funded innovations from the laboratory to the marketplace by reducing the administrative and regulatory burdens for technology transfer and increasing private sector investment in later-stage R&D; developing and implementing more effective partnering models and technology transfer mechanisms for federal agencies; enhancing the effectiveness of technology transfer by improving the methods for evaluating the return on investment (ROI) and economic and national security impacts of federally funded R&D, and in turn, using that information to focus efforts on approaches proven to work.[46]

Research, development, and manufacturing innovations are necessary but not sufficient for the United States to lead in energy storage. DOE will work with other federal agencies to support later-stage activities related to market adoption, such as scale-up, market development, commercialization, demonstration, and deployment, which are critical.

Use Cases. The Use Cases identified earlier in this Roadmap provide illustrative examples of the types of services energy storage may provide now or in the future. These Use Cases can inform the range of business models that may be applicable in various energy storage markets. At the same time, other Use Cases may emerge that create additional business opportunities. The goal of the Technology Transition Track is to explore the full range of commercialization pathways and identify activities to support and potentially accelerate their development.

Addressing Key Challenges through Technology Transition

U.S. economic strength depends on a robust innovation pipeline of new technologies. This requires sufficient investment in early stage technology development, opportunities to demonstrate that technology, and market structures that support predictable long-term revenue streams to attract follow-on investment and reach commercialization.

46 https://www.performance.gov/CAP/lab-to-market/

Innovate Here

As described in the U.S. National Security Strategy:

> *The United States will build on the ingenuity that has launched industries, created jobs, and improved the quality of life at home and abroad. To maintain our competitive advantage, the United States will prioritize emerging technologies critical to economic growth and security, such as data science, encryption, autonomous technologies, gene editing, new materials, nanotechnology, advanced computing technologies, and artificial intelligence.*[47]

This would include strengthening the U.S. innovation ecosystem and the U.S. national security innovation base. To achieve this objective, activities in the Technology Transition Track must identify options for expanding the innovation pipeline and commercializing more technologies.

Financing early stage technologies and companies requires a significant amount of risk tolerance due to uncertainty over market conditions, regulatory considerations, or technology performance. The range of potential applications for energy storage, as well as the numerous technologies that may meet those applications' requirements, leads to a multitude of specific financial calculations to match potential technology to a particular use. This process includes the need for market participants to develop and test out particular business models to attract investors and secure lower cost of capital. These business models, in turn, need a sufficient level of market demand to achieve the scale necessary to ensure revenues exceed costs and thus receive adequate investment.

Additionally, the National Security Strategy lays out an expectation of a nimble innovation enterprise that adapts quickly and rewards risk taking:

> *The United States must regain the element of surprise and field new technologies at the pace of modern industry. Government agencies must shift from an archaic R&D process to an approach that rewards rapid fielding and risk taking.*
>
> *We will improve America's technological edge in energy, including nuclear technology, next-generation nuclear reactors, **better batteries**, advanced computing, carbon-capture technologies, and opportunities at the energy-water nexus. The United States will continue to lead in innovative and efficient energy technologies, recognizing the economic and environmental benefits to end users.*[48]

Intellectual Property (IP) Rights

U.S. leadership in energy storage requires modern and robust Intellectual Property (IP) and related policies to encourage and sustain domestic storage manufacturing. IP and U.S. manufacturing are tied together. As existing energy storage technologies and manufacturing processes are improved and new ones are developed, this creates new IP. For innovations that originate from public support, DOE currently provides mechanisms for transferring this IP to the private sector, including licensing, cooperative research and development agreements (CRADAs), and work for others. Under the ESGC, to the extent permissible by law, DOE will require substantial manufacturing in the United States for

[47] https://www.whitehouse.gov/wp-content/uploads/2017/12/NSS-Final-12-18-2017-0905.pdf

[48] https://www.whitehouse.gov/wp-content/uploads/2017/12/NSS-Final-12-18-2017-0905.pdf

technologies and processes embodying IP developed through DOE investment. In addition, DOE may consider applicants' domestic manufacturing strategies as merit criteria for proposals.

The Energy Storage Grand Challenge may also consider the role of trade policy and international IP rules in achieving U.S. leadership in energy storage.

Make Here

As described in the Manufacturing and Supply Chain (M&SC) section of this Roadmap, domestic manufacturing both supports the U.S. economy directly and is connected directly with the innovation pipeline. Innovation in manufacturing supports the development and commercialization of new technologies. Sufficient investment is required in companies seeking to manufacture domestically as well as in specific manufacturing facilities. However, investment in manufacturing is dependent on a degree of domestic market acceptance and revenue certainty if they are to see significant market adoption.

The commercialization and deployment of new energy storage technologies requires significant private sector investment

The deployment of energy storage technologies at scale requires de-risking projects to attract increasing levels of investment. Sources of risk include technology performance and standards, market development, as well as policy and regulation. By targeting the various sources of risk and reducing them for storage technologies, the government can attract additional investment and accelerate deployment.

Four types of risk require specific attention:

1. Project risk—for specific energy storage projects
2. Market risk—for investors in energy storage projects
3. Manufacturing risk—for companies producing energy storage equipment
4. End-user risk – for individuals or end users expecting a certain degree of utility

One goal of this Roadmap is to identify opportunities for government help to de-risk technologies to accelerate their commercial adoption.

Deploy Everywhere

In addition to continued U.S. leadership in technological innovation and domestic manufacturing, U.S. leadership in energy storage requires a strategy that leverages a range of federal government tools and resources to enable U.S. firms to compete in markets around the world.

Increase the leverage of government funds to support the U.S. economy

The ESGC will pursue a commercialization and deployment strategy consistent with the principles outlined in the National Security Strategy:

> *The U.S. Government will use private sector technical expertise and R&D capabilities more effectively. Private industry owns many of the technologies that the government relies upon for*

> *critical national security missions. The Department of Defense and other agencies will establish strategic partnerships with U.S. companies to help align private sector R&D resources to priority national security applications.*
>
> *The United States will promote exports of our energy resources, technologies, and services, which helps our allies and partners diversify their energy sources and brings economic gains back home. We will expand our export capacity through the continued support of private sector development of coastal terminals, allowing increased market access and a greater competitive edge for U.S. industries.*[49]

Energy storage manufacturing may locate close to market demand. Given the size of the U.S. economy, the United States has the potential to support a significant domestic manufacturing base. This would carry with it the benefits to manufacturing innovation described earlier. Additionally, significant global demand will likely occur *outside* the United States. For the United States to be a global leader, U.S. firms must think strategically about where to locate their manufacturing to be competitive in global markets. Recognition that other countries and firms are likely to pursue similar strategies further complicates how this dynamic will play out.

Additionally, the ESGC will partner with the Department of Commerce to identify international markets where U.S. firms might be competitive, and then strategize how to maximize the opportunity for U.S. firms to succeed in those markets. Use Cases that have a large global addressable market may be of particular significance. Strategies could involve research partnerships with local universities/labs, commercial partnerships with local companies, public-private partnerships with state-owned utilities, and strategically locating pilot projects to gain first-mover status in a new market or region.

Demonstration and deployment of energy storage technologies requires high-quality information to support efficient decision-making as well as sufficient capital with reasonable terms to finance bankable energy storage projects. The Technology Transition Track will work with interagency partners, as well as DOE's Loan Programs Office, which can provide financial mechanisms and approaches to assist with pursuit of domestic or international markets.

Market actors require high-quality information to inform decisions; financing is required to address technical, market, project, and political risk

The National Security Strategy also outlines the need for an in-depth understanding of technology and market trends. The ESGC will develop and disseminate market analysis to pursue this objective.

> *To retain U.S. advantages over our competitors, U.S. Government agencies must improve their understanding of worldwide science and technology trends and how they are likely to influence—or undermine—American strategies and programs.*[50]

A range of stakeholders require high-quality information regarding energy storage markets to inform investment decisions and accelerate the commercialization and deployment of energy storage technologies.

[49] https://www.whitehouse.gov/wp-content/uploads/2017/12/NSS-Final-12-18-2017-0905.pdf

[50] https://www.whitehouse.gov/wp-content/uploads/2017/12/NSS-Final-12-18-2017-0905.pdf

This is why the integration of multiple Use Cases with in-depth market analysis is essential for the development of a robust strategy that maximizes the chance of success. International electricity systems vary widely in their complexity and market information (e.g., there is no electricity system in sub-Saharan Africa that is set up to provide income streams from ancillary services provided by grid storage). Thinking strategically about how different U.S. technologies can be targeted to utilize their strengths in different environments is challenging but essential.

The Technology Transition Track of the ESGC will identify gaps in the data, information, and analysis available to market participants that can inform investment decisions and accelerate technology adoption.

Activities

In addition to activities identified elsewhere in this Roadmap, the Technology Transition Track has identified the following activities to spur domestic innovation:

1. **Enhance external partner access to lab experts, facilities, and IP** to accelerate moving technical innovations to market. The Department works to build relationships between lab experts and entrepreneurs, technologists, and investors in the private sector. The ESGC presents an opportunity to systematically pursue these efforts in the context of energy storage. The Technology Transition Track will work closely with the other ESGC tracks to identify opportunities to connect DOE and National Laboratory expertise with external partners. The Lab Partnering Service serves as a portal to DOE IP, subject matter experts, and facilities. Connecting DOE assets with external parties may lead to accelerated commercialization of energy storage technologies via a range of partnering mechanisms.[51] DOE also directly supports the commercialization of energy storage technologies through the **Practices to Accelerate the Commercialization of Technologies (PACT)** projects that promote the commercialization of technologies developed at the Department's National Laboratories.[52]

   Additionally, the **Technology Commercialization Fund** supports activities across the DOE portfolio that accelerate the commercialization of DOE-developed technologies by building partnerships between DOE applied program offices and external entities.

2. **Develop real-world projects to demonstrate technology, provide data for validation and standardization, and reduce technology risk**. Performance validation, standardization, and demonstration projects can give market participants confidence that an energy storage asset will perform up to expectations and integrate with appropriate infrastructure, thus reducing project risk, lowering project costs, and accelerating market demand. This will help enable bankable projects and predictable revenue streams.

3. **Pursue industry collaboration and interagency engagement** to identify challenges in the marketplace and connect private sector entities with government mechanisms that can address the risk of financing emergent energy storage technologies. The ESGC includes extensive engagement with interagency partners to identify opportunities to collaborate and coordinate

51 https://www.labpartnering.org/

52 https://www.energy.gov/technologytransitions/articles/department-energy-announces-new-projects-promote-technology

activities to pursue U.S. leadership in energy storage and fulfill complementary agency and program missions. DOE will facilitate industry coordination and collaboration with National Labs and state and local entities to accelerate market development, help standardize projects where appropriate, and evaluate financial opportunities and mechanisms. DOE will facilitate connections among our interagency and external partners to explore business cases for consumers, utilities, and manufacturers to pursue near- or at-commercial scale demonstrations.

4. **Industry and Market Analysis**. DOE can accelerate technology commercialization by synthesizing and disseminating the best available energy storage data, information, and analysis to inform decision-making and technology adoption. This work will support the development and tracking of ESGC metrics both for the Tech Transition Track specifically and the ESGC as a whole. In support of this objective, the Technology Transition Track led the development of the *Energy Storage Market Report 2020* that aggregates best-available market data. This report supports a quantitative assessment of the state of energy storage markets and could be updated over time to track changes in those markets.

5. **Data Collection and Analysis.** Data collection and analysis activities help establish clear goals and objectives for the National Laboratories, other partners, and the Department by facilitating the evaluation of best practices and effective metrics. This data supports ESGC metric development, helps track progress to ESGC goals, and informs ESGC strategy.[53]

Measuring Success

The Technology Transition Track will develop and maintain real-world market metrics that inform the ESGC's commercialization efforts as well as the ESGC strategy overall. These include investment, project, and manufacturing data for the range of Use Cases and technologies within the ESGC scope. Market metrics also help to identify new markets relevant to the ESGC.

Metrics for the Technology Transition Track build on and complement other tracks' metrics. Whereas Use Case metrics identify the price required to obtain significant market share and technology cost metrics track the bottom-up cost to manufacture a technology to compete in those markets, Technology Transition metrics assess real world market data to assess and validate the real-world market dynamics into which these new technologies compete.

As the cost of new technologies becomes more competitive with existing market price points, we would expect to see an increase in the size and number of real world projects as well as the corresponding investment in real-world projects and manufacturing capacity. The state of these metrics can then feed back to the other ESGC tracks to validate their assumptions and methodologies and inform strategy over time.

53 https://www.energy.gov/technologytransitions/services/data-collection-and-analysis

Policy and Valuation

Track Overview

Purpose: Energy storage can invigorate the U.S. economy as both an end-use product and a source of industrial competitiveness. Cost-effective energy storage can increase system- and facility-level resilience against a variety of threats, improve the operation and value of existing grid assets, reduce the cost of integrating new assets, catalyze new innovation and commercialization, create a new domestic manufacturing sector, and decrease the overall cost of energy for consumers. However, these impacts can only be realized if storage is appropriately valued, and if policies and regulations reflect that value and incentivize the development, installation, and operation of storage technologies in ways that maximize their benefits to the grid and end-users across the U.S. energy system.

Need: While federal and state energy policies are increasingly supportive of energy storage, the effectiveness of current policies and regulations is limited by the complexity of storage's unique role in the energy system, and by an incomplete understanding of the characteristics of individual storage technologies. In particular, more information is needed to better understand performance characteristics; more effectively plan for and operate storage both within the power system alone and in conjunction with transportation, buildings and other industrial end-uses; and how the different services storage provides can be fairly valued and compensated in a way that incentivizes technologies and projects that provide greatest value to the energy system and its end users. Failure to effectively address these issues will prevent even the most well-intentioned policies from bearing fruit, preventing the full realization of the value of energy storage and slowing the growth of the sector.

Mission: The Policy and Valuation Track will develop a coordinated, DOE-wide program to support effective—and cost-effective—energy storage policies and regulations across the United States through analysis and technical assistance. The program will leverage the Department's unique analytical capabilities, data, and computing resources to develop new data, tools, and analysis that allow energy sector policy and decision makers to maximize the value of storage in the electricity, transportation, buildings, and industrial sectors. As an objective, research-focused organization, DOE will not promote or encourage specific policy objectives. Instead, the ESGC will provide individual policymakers with the information and tools necessary to meet their own objectives as effectively as possible, while also maximizing the value of energy storage.

What is the role of the government? What is DOE's role? The federal government and DOE act as an objective, credible, and technically-savvy third party to deliver data, tools, and analysis to a wide range of stakeholders. The ESGC will utilize DOE's unique convening capabilities to sustain engagement with stakeholders in order to identify key issue areas and prioritize analytical activities.

Policies and regulatory decisions affect each of the three key challenges of the ESGC: **innovate here, make here,** and **deploy everywhere**. Figure 9 illustrates how effective energy storage policies can accelerate innovation, bolster manufacturing, and remove market obstacles while simultaneously augmenting the demand for storage, which grows the market, enables economies-of-scale/learning-by-doing, and drives down the cost of energy storage technologies.

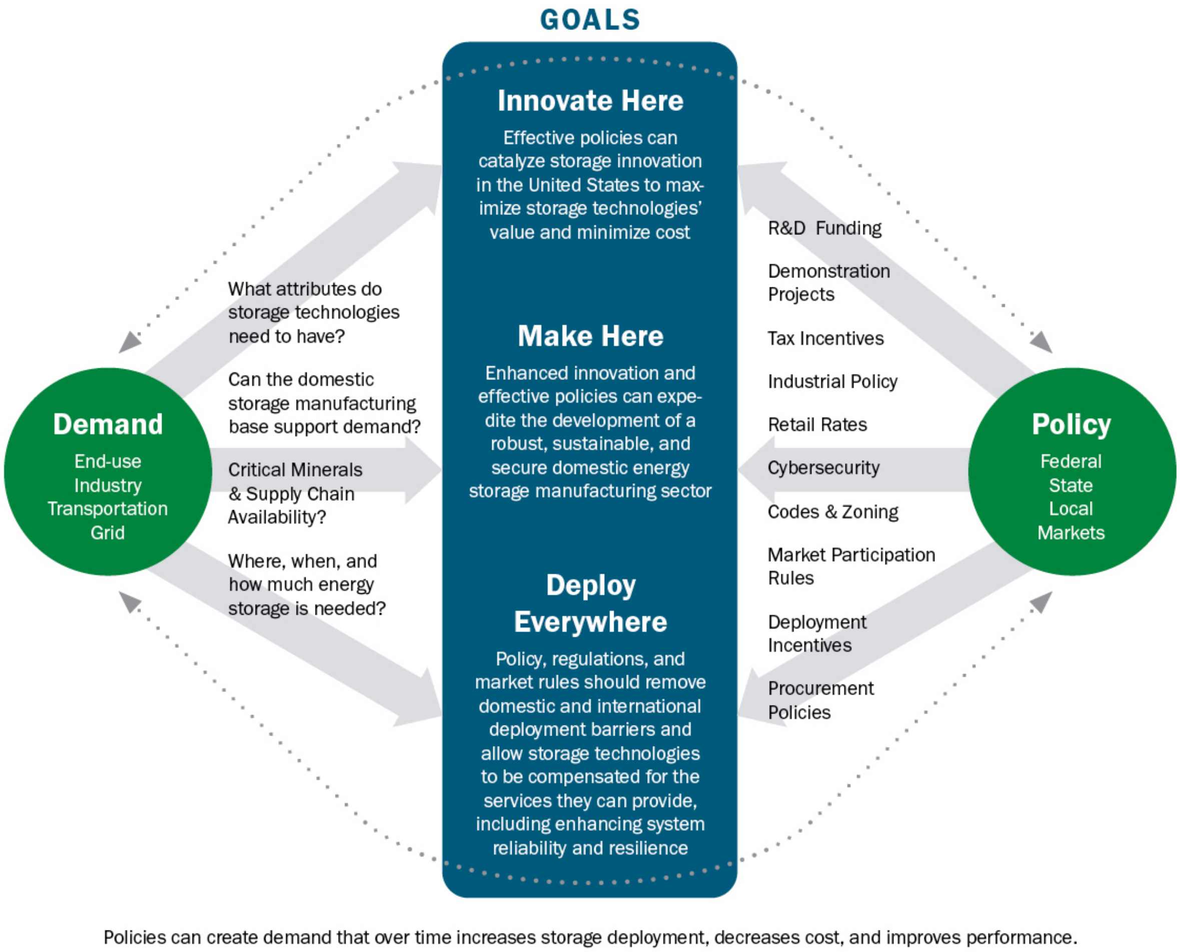

Figure 9. Policy and Valuation: Innovate Here, Make Here, Deploy Everywhere

To have an impact, DOE-supported data and analysis must be effectively disseminated to the full range of policymakers whose decisions will determine the industry's trajectory in the United States. This dissemination will be most effective if delivered through repeated, direct engagement that is targeted, systematic, coordinated, and reciprocal.

- **Targeted**: focused at the most pressing policy, regulatory, and market barriers.
- **Systematic**: proactively working with decision makers to identify and provide all the information needed to enable effective decisions rather than ad hoc support for the easiest issues to address.
- **Coordinated**: to ensure the right areas of expertise are applied to a given question and the Department does not provide conflicting information on a given topic.
- **Reciprocal**: continuously updated and informed by the evolving challenges and concerns of decision makers, which then help prioritize future DOE efforts.

Coordinating activities across the Department will be crucial for maximizing the ESGC benefits for stakeholders. For example, many offices and programs across DOE undertake analytical work related to the role of storage in the grid, buildings, and transportation, but these efforts may not always be mutually informed or aligned. The Policy and Valuation Track will coordinate these disparate analytical and technical assistance efforts to ensure DOE support is both comprehensive and consistent. Specifically, DOE will work with stakeholders to develop a single of point of contact that can then internally coordinate across DOE and the National Labs to align data, tools, and analysis with stakeholder needs as well as avoid unnecessary duplication or conflicting messages. This streamlined structure leverages the same deep analytical and policy expertise found in each of the relevant offices and programs but brings them together, where appropriate, into multi-office teams, or coordinates individual office flagship projects with complimentary efforts in other parts of the Department.

Addressing Stakeholder Impacts and Challenges

A wide range of policy, regulatory, market, and consumer decisions impact the deployment, use, and value of technologies in the U.S. energy system. The continued rapid evolution of individual storage technologies and the energy system as a whole has made it difficult for stakeholders to ascertain:

- **What can storage do?** The technical performance capabilities (under different Use Cases) and life cycle costs of different storage technologies are required to make optimal investment and operational decisions.
- **What is the most effective way to plan for and operate storage?** Storage should be effectively incorporated into planning processes to ensure its optimal contribution to resource adequacy, efficient dispatch, power system stability, enhanced mobility, and resilience.
- **How can storage be fairly valued and compensated?** Ownership structures, participation models, and market products should appropriately compensate storage for the services it provides the grid and end users.

This lack of information affects many different decision makers, each with a critical role in valuing energy storage. If stakeholders can't answer these questions and ultimately make uninformed decisions, it may lead to limited energy storage technology deployment, suboptimal grid operation, decreased system resilience, inefficient utility, developer, and consumer investment, and an inability to develop a robust, secure domestic energy storage manufacturing sector. Descriptions of stakeholders and the potential impacts they can have on energy storage deployment, use, and value are listed in Table 6.

Table 6. Policy Valuation stakeholders and potential impacts

Stakeholder	Role	Impact with Enhanced Information and Tools
Governors, State Legislatures	Consider a broad range of energy policies (weighing costs and benefits), e.g., procurement targets, directions for new or existing regulations, create and fund demonstration programs, consider financial and non-financial incentives, and require consumer protections.	Enact policies that ensure stationary and transportation-related storage is valued appropriately to advance energy objectives, reliability, and resilience at the lowest possible cost to consumers.
State Energy Offices	Implement energy policy, develop plans, and conduct analysis in support of governors and legislatures; engage with other stakeholders to plan and implement energy policy and programs; plan for energy emergencies; and develop and implement standards and codes in a wide variety of areas (e.g., buildings, cybersecurity, recycling).	Better able to value both stationary and transportation-related energy storage technologies in planning efforts and analytical products, enabling improved policy design and implementation in support of governors' and state legislatures' priorities.

Stakeholder	Role	Impact with Enhanced Information and Tools
Public Utility Commissions	Review and approve retail rates, planning and (grid/transportation) investment decisions, as well as other regulations for investor-owned utilities to ensure just and reasonable costs are passed on to consumers, while also considering the needs of the grid.	Create just and reasonable rate structures that both appropriately value and compensate stationary and transportation-related storage technologies for the services they provide as well as align customers' desire to own their own power systems and have bill certainty/control with utilities' requirements for reliable operations and revenue sufficiency. Improved oversight of utility planning for and investments in stationary and transportation-related storage infrastructure.
FERC ISO/RTOs	FERC regulates interstate wholesale electricity sales and other interstate energy infrastructure projects. ISO/RTOs are independent entities that plan, coordinate, and operate regional electric grids, transmission, and power markets.	Implement transparent, technology-agnostic requirements for market participation that enable storage technologies to provide and be compensated for their full range of services.
North American Electric Reliability Corporation (NERC)	NERC develops and enforces Reliability Standards; annually assesses seasonal and long-term reliability; monitors the bulk power system through system awareness; and educates, trains, and certifies industry personnel.	Assures the effective and efficient reduction of risks to the reliability and security of the grid, by ensuring the optimal integration of energy storage technologies.
Utilities	Utilities conduct planning processes and make investments to ensure power can be cost-effective and reliably procured, transmitted, and distributed to end-use customers.	Update planning processes to evaluate the potential for storage technologies and the evolving technology mix in the distribution and transportation sectors, making more cost-effective investments to ensure reliability and resilience, and save customers money.
Tribal Governments	As sovereign entities, tribal governments have the ability set long-term energy goals, conduct planning and procurement assessments, as well as invest and operate energy generation, storage, and transmission assets.	Implement energy storage solutions that can increase the reliability and resilience of their energy system while decreasing cost to users.
Mayors, City Council Members, Resilience & Sustainability Offices	Consider a broad range of energy policies (weighing costs and benefits), e.g., procurement targets, create new or revise existing regulations, create demonstration programs, implement financial incentives, etc.	Consider local policies that ensure stationary and transportation-related storage can be cost-effectively installed, operated, and recycled to promote policy objectives, reliability, and resilience at the lowest possible cost to consumers within their jurisdictions.
Municipal Planning & Zoning Bodies	Control highly localized yet impactful rule making, including zoning and building codes that impact how storage can be sited inside or next to buildings, safety and fire codes, etc.	Stationary and transportation-related storage projects can be safely sited in appropriate areas and provide value to a wide array of stakeholders.
Technology Developers	Create and manufacture energy storage technologies, controls, and communications equipment and software, as well as other supporting equipment and infrastructure.	Stationary and transportation-related storage technologies are designed and manufactured to provide maximum societal benefits and services given safety, environmental, and other market regulations. Storage products are also optimized to consider end-of-life issues.
Investors	Provide financial backing for both start-up and mature technology developers, manufacturers, and project developers.	Investments are well informed and focus on stationary and transportation-related storage technologies and manufacturing processes with a high probability of being cost-competitive.
Project Developers	Engineer, procure technologies and software, invest, and ultimately construct storage projects. Includes stationary storage but also	Storage projects and infrastructure are configured to maximize value to the grid, end-use consumers, and the project developer.

Stakeholder	Role	Impact with Enhanced Information and Tools
	infrastructure for transportation-related storage.	
Consumers	Procure stationary or transportation-related energy storage systems to decrease cost and increase bill certainty/control, or enhance the reliability and resilience of their home, business, facility, industry, or community.	Make cost-effective investments that allow end users to accomplish their goals at the lowest possible cost.
DOE R&D Organizations	Prioritize and fund activities that can drive down cost and de-risk energy storage technologies.	Innovators focus on technologies and applications that are of highest value, leading to faster commercialization pathways.

Stakeholders identified four specific policy and valuation key issues areas and four foundational needs. Each Policy and Valuation issue area intersects with each foundational need and is described below. Figure 10 describes how the policy and valuation key issues and needs support the six Use Case families developed in the Technology Development Track.

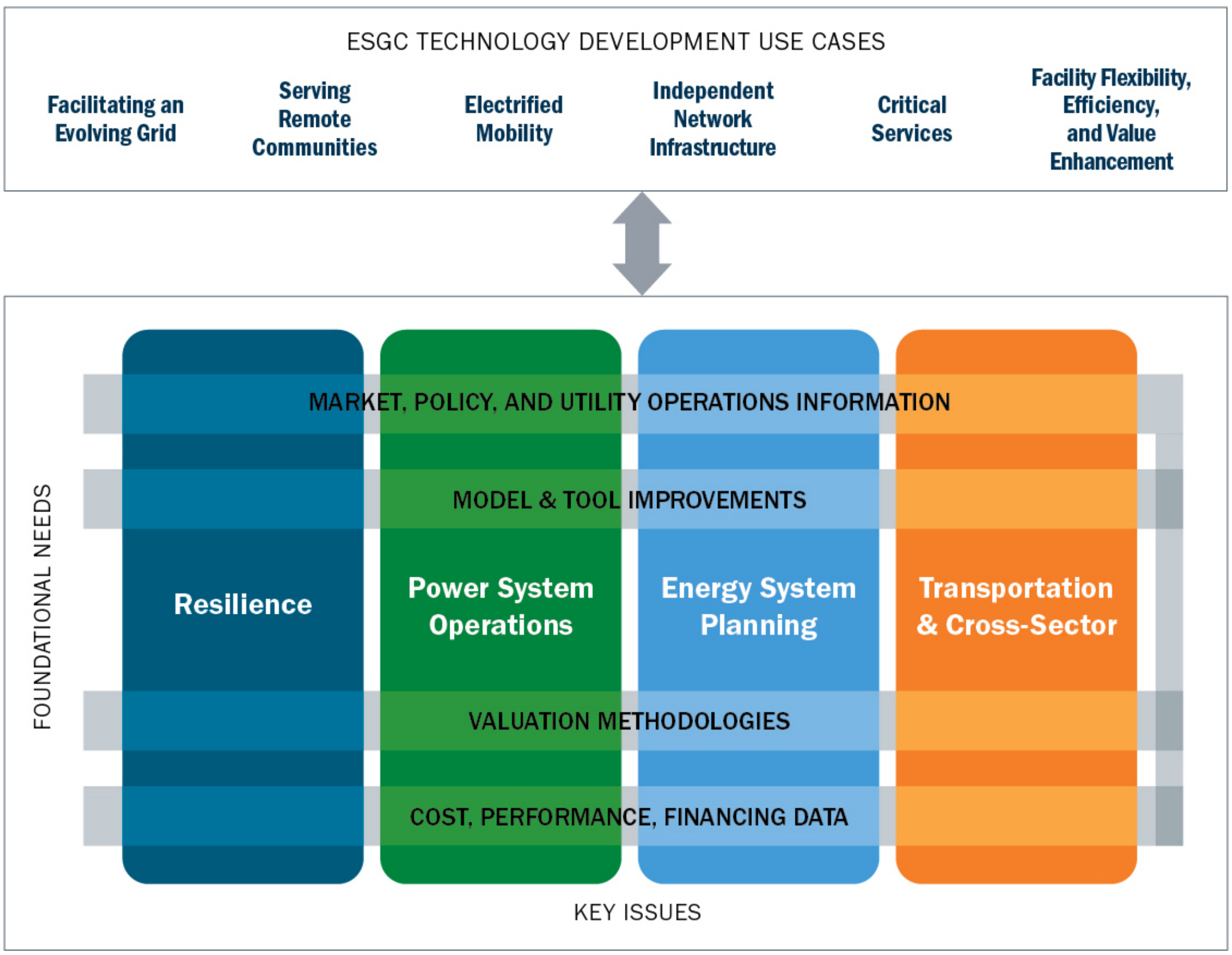

Figure 10. Relationship between Technology Development Use Cases and Policy and Valuation key issues and needs

Four Key Priority Issue Areas

1. **Resilience** is one of the most pressing and least understood challenges facing the energy system today. It is the ability of a system to recover from and resume normal operations after a disruption (as opposed to reliability, which is the ability of a system to mitigate or avoid disruption). Resilience is commonly identified with attributes such as resourcefulness, redundancy, robustness and recovery and is distinct from reliability, which addresses short-term power quality issues.[54] It is critical to identify what characteristics a resilient system has and develop a robust methodology to measure energy storage technologies' ability to improve system and end-use resilience against low-frequency, high-impact events. For example, how can storage technologies provide backup power during outages to minimize financial, health, and safety impacts; and can energy storage help with restoration activities (e.g., black start)? Assessing energy storage's resilience contributions will also need to account for different threat types, probabilities, outage durations, costs, and system or facility characteristics.
2. **Power system operations** are essential for maintaining the reliability of the grid. The representation of storage technologies (including hybrid configurations) in operational planning processes and power flow, system stability, and optimal dispatch tools needs to improve. These tools should also capture dynamic interactions between the distribution and bulk-power systems, specifically focusing on distributed energy resource and transportation-related storage adoption and infrastructure requirements.
3. **Energy system planning** is needed to identify how much, where, and at what duration future distributed energy resource (DER), bulk-power, transmission, non-wire-solutions, and transportation-related storage assets are needed. Key questions include: what kind and what amount of demand-side resources are useful if there is significant storage deployment? What kind and amount of storage is needed if load flexibility dramatically increases? To facilitate this integrated planning, new tools and processes could rapidly update technology cost and performance assumptions, model interactions between the distribution, bulk-power, buildings, industrial, and transportation sectors as well as account for different generation mixes, technology and fuel availability, infrastructure buildouts, and changing weather conditions. Near-term tools should also allow users to identify optimal storage siting and sizing for individual facilities or systems.
4. **Transportation and other crosscutting issues** address questions such as how can transportation-related energy storage systems (electric and fuel cell vehicles) provide flexibility and services to the grid and other end-users? How do we expect consumers to adopt and use these vehicles? Can storage enable increased charging and refueling infrastructure to be cost-effectively integrated into the existing system? What are the cost and performance interactions between the transportation and stationary storage systems? How can new types of energy storage (hydrogen, ammonia, methanol, etc.) be valued, especially if they have end-use applications and interactions/interdependencies across sectors? What are the commercial pathways for these technologies? How can storage be integrated into industrial processes to

54 For more information on a comprehensive resilience evaluation framework, see the Federal Energy Management Program's Technical Resilience Navigator (https://trn.pnnl.gov/).

decrease unexpected downtime from outages, decrease fuel price risk, decrease waste heat, and assure power quality? What types of policies can most efficiently support a robust, sustainable, and cost-competitive domestic energy storage manufacturing sector? How can supply chain bottlenecks constrain the deployment of different energy storage technologies, and how can they be avoided?

Four Foundational Needs

1. **Cost/price, performance, and financing data**. The need is to develop a centralized, validated, open-access database that tracks technologies' current CapEx, OpEx, and financing (Weighed Average Cost of Capital debt-to-equity ratio) data given associated system size and resource quality; and, provides transparent projections of storage technologies' future costs considering uncertainty. For nascent technologies, clearly identify the potential cost and performance impacts of R&D improvements and how economies of scale can drive cost reductions and performance improvements. Identify storage technologies' attributes (duration, ramp rate, response time, etc.) and how duty-cycles can have non-linear impacts (operation, temperatures, chemistry, auxiliary loads, depth of discharge, etc.) on long-term performance and degradation. Validate modeled cost, performance, and finance data against real-world data via a wide range of retrospective analyses for each type of storage technology. Work with owners, operators, and OEMs to overcome IP and other proprietary sensitivities.

2. **Valuation methodologies**. The need is to consistently classify what services and other non-monetized benefits different stationary and transportation-related energy storage technologies can provide and their value, given system, infrastructure, and market characteristics. Valuation methodologies should also be readily accessible to a wide variety of stakeholders (developers, utilities, end users, regulators), account for different ownership types (e.g., grid planners need to optimize for system value while also accounting for revenue requirements/cost savings from the asset owner's perspective), and include materials processing impacts, manufacturing impacts (energy and environmental), end-of-life costs, recycling costs/potential, material recovery potential, etc.

3. **Tools** are essential for quantifying the potential impact energy storage technologies have on both power system operations and energy system planning. Tools that inform energy storage decision making should have enhanced geographic resolution to optimize the locational value of storage deployment; improved temporal resolution (sub-second, minute, hour, month, year, and multi-year) to ensure we can assess the full range of potential services storage technologies can provide; dynamic representation of operational profiles on storage system's efficiency, degradation, cost, and performance; ability to value hybridized storage systems that include different technologies and linkage-configurations; and account for uncertainty. The need is to move away from perfect foresight to stochastic optimization to mimic real-world risks that investors and operators face; use open-source code and publicly available data to ensure tools can be used by a wide variety of stakeholders; and gain ability to compare results between tools to understand inherent biases of models, methodologies, and data suites.

4. **Markets, policy, and utility operations information**. Understanding the federal, state, and local policy and regulatory landscape is critical for understanding energy demand and how stationary and transportation-related energy storage will be operated, what services storage can provide

and be compensated for, and how valuable storage will be relative to alternative technologies. Also, the need is to understand near-, medium-, and long-term market issues for vertically integrated utilities and competitive power markets that can impact storage (interconnection processes, participation models, asset classes, planning requirements, etc.).

Activities

The Policy and Valuation Track will support stakeholders by addressing the four key issue areas and foundational needs identified in the previous section. This support will be delivered through systematic engagements with key energy sector decision makers. Sustained engagement will allow the best-in-class data, tools and analysis developed through the ESGC to be tailored to specific needs and challenges facing each type of stakeholder, and for the information developed by DOE to be disseminated effectively and put to use. ESGC-driven analysis will provide insights into the key questions stakeholders are facing related to effective storage policy, regulations, and planning decisions. DOE will work with stakeholders to help enhance off-the-shelf commercial planning tools while simultaneously improving existing National Lab models or developing new open-source tools that can accurately represent storage's unique performance characteristics and potential value streams. DOE will also collect, validate, and share data related to current and future stationary and transportation-related energy storage, cost, and performance to ensure all stakeholders evaluate potential storage options on a level playing field. Near-term Policy and Valuation Track activities developed with input from industry, policymakers, and other stakeholders are listed in Table 7 and are mapped onto the Policy and Valuation Track's key issue areas and foundational needs in Figure 11.

Table 7. Near-term Policy and Valuation activities

Activity	Description
Energy Storage Cost and Performance Database	• Develop a common nomenclature for energy storage cost components and cost metrics. • Track the current and estimated future cost and performance estimates for a wide array of energy storage technologies. • Work with industry and the National Laboratories to validate data while respecting proprietary information. • Regularly updated data and methodology will be available for download on a public website.
Grid Services Taxonomy	• Develop a taxonomy of grid services that explains their technical requirements, how they differ by market, whether they are currently compensated or non-compensated, and how they might change in the future.
Estimating the Value of Utility-Scale Storage under Different System Conditions	• Use new modeling capabilities to quantify and disaggregate the different value streams energy storage technologies can access in different regions and different market types, under a range of different potential scenarios.
Distributed Energy Resource Valuation on the Distribution and Bulk Power System	• Develop methodology to assess the impact of multiple DERs (including storage) on residential load profiles in order to assess DERs overall cost and reliability impacts on both the distribution and bulk-power systems.
Tool Development and Model Benchmarking	• Develop a formalized process for tool validation and comparison activities with National Labs and industry. • Work directly with end-users and vendors to ensure developed tools meet user requirements and can be integrated into planning processes.
Tracking Energy Storage in Resource Planning Processes	• Work with industry to track what types of assumptions, methodologies, and tools are being used to represent energy storage in IRP processes to better provide data, tools, and analysis that help states and utilities make informed decisions to meet their priorities.

Activity	Description
Supporting Market Design Analysis	• Work with existing ISO/RTOs, power sector, and research partners to identify salient energy storage issues facing wholesale electricity markets. • Provide data, tools, and other analyses to help stakeholders assess different potential market outcomes.
Supporting Integrated Cross-Sectoral Resource Planning	• Develop a report outlining best practices and other strategies to help utilities, regulators, and other entities coordinate and optimize planning processes across multiple sectors, e.g., integrating distribution, transportation, and bulk-power system planning.
Energy Storage Policy Database	• Enable easy comparison of different enacted policy types (mandate, incentives) and design choices, to enable stakeholders to learn directly from each other. Database will not endorse or recommend any policies, just provide factual information.
Resilience Valuation Workshop	• Hold a workshop with industry, regulatory, and National Lab partners to identify 1) existing state-of-the art for resilience valuation methodology, 2) areas where data, models, and planning processes need to be improved, and 3) other barriers preventing entities from effectively valuing resilience. The workshop will allow DOE to synthesize existing methods, better prioritize high priority issues, and internally/externally coordinate resilience activities.
Annual Storage Policy and Valuation Workshop	• Hold an annual workshop to disseminate the latest data, tools, and analysis related to the ESGC's Policy and Valuation Track. • This forum will also provide another venue for stakeholder to provide feedback about their ongoing data, tool, and analytical needs with the ESGC and each other.

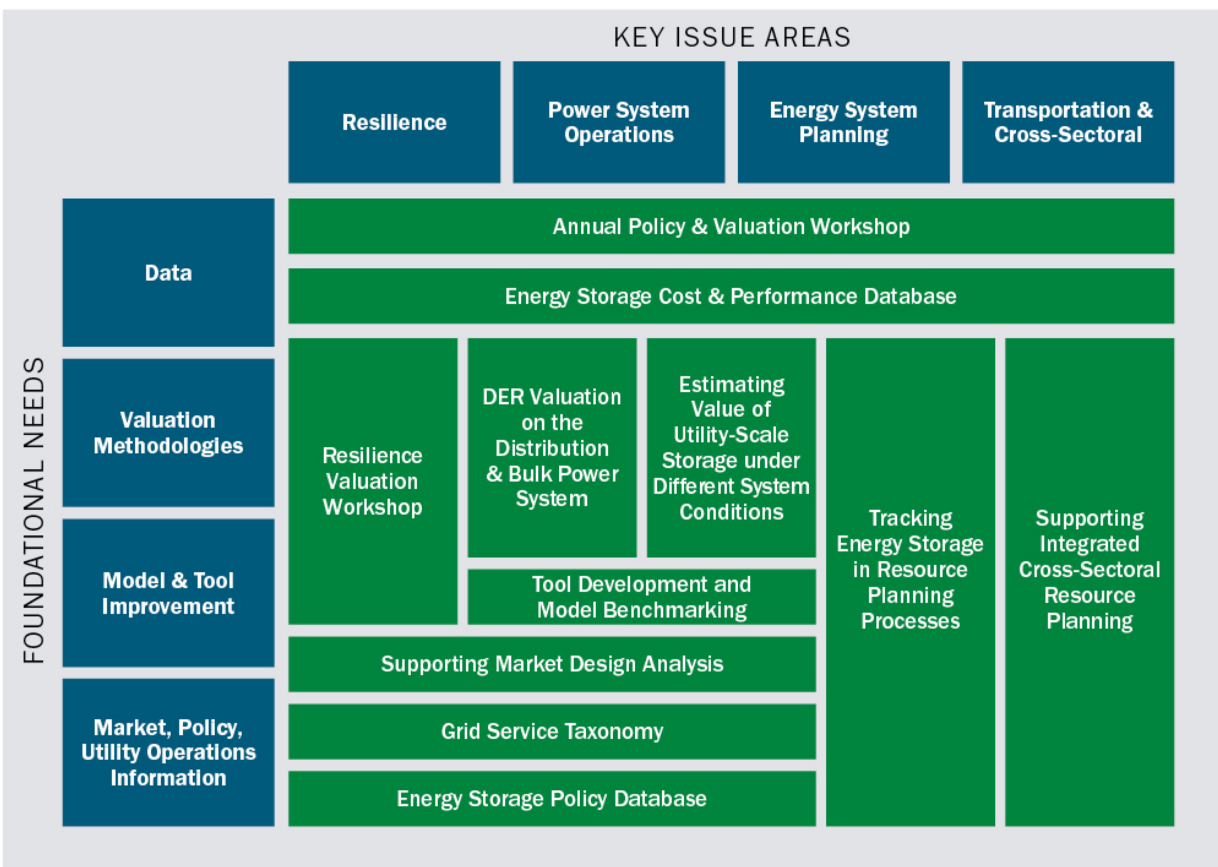

Figure 11. Mapping near-term activities to Policy and Valuation key issue areas and foundational needs

ESGC analysis will focus on both near-term and long-term storage and energy systems questions. All stakeholder engagements and analytical work will be coordinated across DOE and the National Labs to ensure consistent methodologies, assumptions, and tools are used when appropriate. Much of the analysis informing this programmatic support will be relevant to a wide range of different stakeholders—for example, utilities and regulatory commissions are often looking at a similar set of questions—and the analysis will be based on up-to-date data and improved models and analytical tools.

While the Policy and Valuation Track's main focus is energy storage, it recognizes that no single power system technology can be evaluated in isolation—the value and optimal integration of energy storage is system-specific and determined by the characteristics of the system in question. As a result, analyses will consider other sources of system flexibility and approaches to power system planning and operation, including distribution system changes, demand-side resources, grid architecture evolution, and cybersecurity, as each of these will impact how storage is designed, constructed, deployed, and valued.

For a detailed list of ongoing Policy and Valuation activities being coordinated across the Department, see Appendix 4.

For a description of key cost of performance metrics that impact how energy storage systems may be valued, see Appendix 5.

For descriptions of currently enacted federal and state regulations that may impact how energy storage is operated, deployed, and valued, see Appendix 6.

Measuring Success

The Policy and Valuation Track will be successful if policy makers, regulators, utilities, and other stakeholders have the data, tools, and analysis required to make informed decisions that enable the United States to become a leader in energy storage research, manufacturing, deployment, and export.

In order to achieve this outcome, the Policy and Valuation Track has two overarching goals:

1. Provide stakeholders with the data, tools, and analysis to make informed energy decisions. Specific sub-goals include:
    - By 2021, develop standardized energy storage cost and performance nomenclature and a publicly available website and dataset that describes the current and future cost and performance characteristics of six energy storage technologies, including metrics specific to each Technology Development Track Use Case. By 2025, expand the dataset and website to include at least 18 energy storage technologies. By 2030, characterize and track any other novel storage technologies that were not previously captured and are being researched by DOE.
    - By 2025, double the number of utilities that have access to, and include up-to-date energy storage data in their integrated resource plans. By 2030, ensure all utilities, state regulators, and ISO/RTOs have the information required to include both short- and long-duration energy storage technologies as well as demand-side flexibility solutions (managed EV charging, etc.) in their long-term energy planning processes.

   - By 2025, represent energy storage technologies including demand-side flexibility (electric vehicles, demand response, etc.) in open-source power sector models with five minute to sub-minute temporal resolution, agent-based decision making, and real-world market constraints. By 2030, deploy an integrated modeling architecture with dynamic, cross-sectoral supply and demand interactions that is scalable across sectors, geographies, and timescales.

2. Use cutting edge analytical resources to track the competitiveness of various energy storage technologies and help prioritize DOE's future R&D and technical assistance plans.

   - By 2025, use the new data, valuation methodologies, and tools developed in the Energy Storage Grand Challenge to down-select to three potential energy storage technology pathways for each Use Case developed in the Technology Development Track. By 2030, identify the most promising near-term technological solutions for each Use Case.

Workforce Development

Track Overview

Purpose: Focus DOE's technical education and workforce development programs to leverage existing resources to train and educate the workforce, who can then research, develop, design, manufacture and operate energy storage systems widely within U.S. industry.

Need: The lack of trained workers has been identified as a concern for growth of the U.S. industrial base, including many areas of energy storage. To have world-leading programs in energy storage, a pipeline of trained research and development staff, as well as workers, is needed.

Mission: For workforce development in energy storage, DOE will support opportunities to develop the broad workforce required for research, development, design, manufacture, and operation.

What is the role of government? What is DOE's role? The Department of Energy can play a critical role in facilitating the development of a workforce that is necessary to carry out DOE's specialized mission. Energy storage is a highly specialized area of work that requires skills and expertise in multiple disciplines across the spectrum from theory to practice, and yet the necessary education and training elements are currently limited or not available in 2- or 4-year college curricula. Therefore, it is appropriate that the DOE take the lead in strengthening a pipeline of qualified individuals who can fulfill employment needs at all stages of energy storage development, production, and deployment.

Addressing Key Challenges through Workforce Development

In order to maintain global leadership in energy storage, the United States will need to develop and maintain a well-qualified workforce in the right areas in a timely manner at all levels of education.

Innovate Here: To maintain global leadership in storage R&D, DOE's ongoing efforts will be leveraged to grow the pipeline of candidates qualified to lead the field in research. This includes supporting innovative research at universities and National Laboratories, along with building and operating world-class user facilities, all of which help train the workforce of the future.

Build Here: As illustrated by the diversity of the Use Cases, there is a wide range of potential technology requirements spanning from small to large systems; factory built to bespoke, site-built installations; and chemically to thermally based storage. For the United States to lead in these technologies, there will be a need from trades (machinists, welders, designers), to engineers (mechanical, chemical, electrical) to research scientists (materials science, chemistry).

Deploy Everywhere: To build, use, and maintain energy storage systems as an integrated part of our country's energy systems, there will need to be a workforce that can understand how these pieces fit together and can be optimized for the particular application. This will require not just technicians, operators, and engineers, but analysts who can model and optimize these systems.

Impact

Leadership in storage requires a skilled, nimble, and innovative workforce. The ESGC can impact the development of the workforce through activities outlined below such as skills development and enhanced employment opportunities. Similarly, the development of a workforce with the appropriate skill set can allow industries such as battery manufacturers, chemical producers, and utilities to increase national leadership in these areas.

One key aspect to developing a workforce is generating excitement about the field. If students or trade professionals feel there is a lack of jobs in a specific topical area, or if the topical area does not generate an excitement among potential workers, then they will not pursue the educational opportunities needed to fill the workforce needs. The ESGC can serve to provide the visibility and excitement at all levels of education. This will help persuade people that there will be work in these specialties.

The industry and workforce must develop hand in hand. As the industry grows, there will be more opportunities for a skilled workforce across a wide range of skill sets. These will include trade professionals, chemical engineers, mechanical engineers, and scientists from a host of disciplines. The ESGC will enable the development of an appropriate workforce of the future through programs across DOE targeted at the spread of workforce development needs.

Activities

It is clear that to grow and strengthen the energy storage industries in the United States, the existence or development of a strong and dedicated workforce will be a key building block for success and DOE has a key role to play in that effort.

Stakeholder workshops and the RFI have provided input regarding the primary workforce gaps that would impact the development, production, installation, and use of energy storage systems. DOE programming in relevant Offices can build upon ongoing DOE workforce development activities related to energy storage. These activities have benefited from input from a wide variety of stakeholders over the years.

As research, development, and implementation of energy storage across sectors has increased over the past decade, DOE has recognized the need for workforce development for energy storage and has built several programs that feed this pipeline, which are outlined below. Continued work can build a sufficient workforce to serve the future energy storage sector in the United States.

The DOE runs more than 50 Education and Workforce Development programs or activities that facilitate an increased specialized knowledge, spanning middle and high-school (National Science Bowl®), all levels at 2- or 4-year colleges/universities including faculty (Science Undergraduate Laboratory Internships, Community College Internships, EERE Energy Storage Internships, Science Graduate Student Research Program, Computational Science Graduate Fellowships, Visiting Faculty programs), and broader professional workforce development activities (Industrial Assessment Centers, Lab-embedded Entrepreneurship Program). Several of these focus on or have an explicit component relating to energy storage. Many others do not but could serve as templates for future workforce development programs related to energy storage.

One current program with a specific energy storage component is the Office of Science Graduate Student Research Program,[55] which has a topic relating to energy storage and enables graduate students to spend a portion of their graduate research effort at a National Laboratory. Another targeted program, the EERE Energy Storage Internship Program,[56] will provide undergraduate and graduate students an opportunity to spend 10 weeks during a summer at a National Laboratory working on energy storage-related projects under the mentorship of lab researchers.[57]

Several DOE programs in workforce development for college students do not currently focus on energy storage, but they could serve as launch points for future activities in response to stakeholder feedback. Currently, DOE and the National Laboratories offer development opportunities for students at all levels, often as interns, graduate students, and postdoctoral staff, in the full range of energy-related technology development including energy storage broadly. These include hands-on opportunities to work on real problems from an interdisciplinary prospective. Large research consortia (including Hubs, Energy Frontier Research Centers, and Manufacturing Institutes) have strong student participation and internship opportunities that train students for employment in energy fields for industry, academia, and National Labs. Additionally, DOE-supported user facilities include significant numbers of students and postdoctoral fellows as participants in research.

There are a number of relevant programs under the Office of Science's Office of Workforce Development for Teachers and Scientists, [58] which sponsors students from community colleges, undergraduate and graduate students, and faculty to participate in DOE National Laboratory research. The faculty and students may work on projects with scientists and engineers at DOE national laboratories in areas focusing on or related to energy storage.

In the Advanced Manufacturing Office (AMO), the Manufacturing USA institutes support education and workforce development programs relevant to their technologies. Some of the more successful approaches have been hands-on training and web-based training as well as traditional classroom-based skills development. AMO has learned that Education and Workforce Development programs are most effective when tailored to the technology domain and to the needs of industrial partners. These and other potential programs will be explored to find those most appropriate for energy storage.

The largest footprint in DOE's workforce development is with graduate students and post-doctoral researchers supported through grants for research and technology development, as is appropriate for a research agency. There is also substantial involvement of undergraduates in projects at universities and National Laboratories. These workforce development activities, both specific programs and inherent training as part of ongoing research projects, span the breadth of DOE's research. The student interaction with the National Laboratories through these projects provides a broader educational opportunity to complement what may be limited or unavailable in universities but in demand by stakeholders.

55 https://science.osti.gov/wdts/scgsr

56 https://www.zintellect.com/Opportunity/Details/EERE-2020-EnergyStorage

57 As of this writing, most labs are still planning to participate despite the current closures due to COVID-19, though some may need to provide "virtual" experiences.

58 https://science.osti.gov/wdts

While the DOE has a broad range of workforce development activities as outlined above, there are opportunities to provide more emphasis and focus on energy storage as a topic. Therefore, the ESGC will develop increased insight into current gaps in these areas and then build upon DOE's existing activities related to workforce development with the following specific activities:

1. **Seek detailed stakeholder input on workforce gaps and needs.** The ESGC will continue to solicit feedback from relevant stakeholders on workforce development issues through ongoing stakeholder engagement across a broad spectrum of energy-storage related industries. Input from stakeholder meetings and the RFI pointed to several critical education and training gaps (for example, specific electrochemistry-focused curriculum/major, more interdisciplinary oriented education) and opportunities (such as experiential learning, involvement of Opportunity Zones, growth of programs at Historically Black Colleges and Universities as well as other minority-serving institutions, and development of programs in Native American communities). A training model based upon strategic partnership between universities, National Laboratories, and industrial companies was considered promising. While some of these are outside the direct purview of the DOE, the ESGC will raise the visibility of these opportunities to the relevant stakeholders.
2. **Conduct a Needs Assessment/Skills Assessment**. Conduct an inventory and analysis of existing DOE Education and Workforce Development Programs in areas of energy storage and the related technologies. This will include activities at all education levels and target audiences. The effort also will include assessment and evaluation of effectiveness of these programs. The outcome of this effort will be used to help identify opportunities for enhancing or expanding programs in addition to identifying gaps where new programs can be supported.
3. **Enhance opportunities for innovation in workforce development**. An enhanced focus on energy storage in workforce development activities will broaden awareness of existing programs and encourage cross-communication with the other tracks of the ESGC. In addition, new programs could invigorate the community and spur broadened awareness of energy storage challenges and workforce development needs required to meet critical community needs. These include those involved in trades (apprenticeships for machinists, welders, technicians, designers), engineering (mechanical, chemical, electrical, manufacturing), and scientific research.

Measuring Success

Workforce development programs could be evaluated in several ways to ensure they are being successful. Ultimately the goal is that technology development and deployment under the Uses Cases would not be constrained by workforce needs. There should be a sufficient number of people with adequate training and experience to staff the research, manufacturing, and deployment needs required to meet the Use Case metrics.

As programs in energy storage are further developed in DOE, their success towards these goals can be measured by hiring metrics (availability of a workforce), number of students achieving degrees or certificates in high-demand areas, and growth in targeted demographics and geographic areas. The efficacy of the programs can be evaluated by mechanisms such as surveys over time, focused on the specific stakeholder (universities, industry, research labs, utilities), that are targeted by the program.

Performing a relevant baseline study ahead of starting a new workforce development effort should be a best practice in DOE. In addition, community awareness of the different programs needs to be tracked to ensure an increasing impact of the DOE workforce development activities, which need to reach the broadest possible audience. Some targeted advertising/outreach may be necessary.

Conclusion

As discussed throughout the Roadmap, DOE intends to implement a suite of actions to position the United States for global leadership in the energy storage technologies of the future. The key actions for each track are summarized below:

Technology Development

1. Maintain a set of Use Cases that describe long-term stakeholder objectives.
2. Develop standardized metrics and tools that facilitate technology-agnostic cost and performance evaluations. Develop functional performance targets to inform a long-term R&D strategy that incorporates the Manufacturing and Supply Chain Track's goals of domestic manufacturability (in coordination with Policy and Valuation Track).
3. Accelerate technology development pathways through:
    - Maintaining basic and early stage R&D for a variety of technologies
    - Investing in capabilities that reduce the cost and time to validate new concepts
    - Developing methods and validating data to confirm commercial viability.

Manufacturing and Supply Chain

1. Develop a deep understanding of technical barriers in production and manufacturing for a wide range of energy storage technologies, identifying key technical metrics.
2. Support innovations to lower manufacturing cost and overcome technical barriers.
3. Accelerate scale-up of emerging manufacturing processes through partnerships with industry, and expand U.S. capabilities for testing/validating manufacturing innovations at commercial-scale.
4. Standardize systems design and testing protocols to streamline integration of manufacturing innovations for emerging storage technologies.
5. Deepen understanding and pursue innovation to improve domestic supply chain resilience, and advance processing and separations to diversify critical materials sourcing and improve recycling.
6. Establish a domestic battery manufacturing ecosystem.

Technology Transition

1. Enhance external partner access to lab experts, facilities, and intellectual property (IP) to accelerate moving technical innovations to market.
2. Develop real-world projects to generate data for validation and standardization and reduce technology risk.
3. Pursue industry collaboration and interagency engagement to inform the ESGC strategy to accelerate commercialization and deployment of energy storage technologies.

4. Provide industry and market analysis to support investment, market formation, and policymaking activities.

5. Expand data collection and analysis activities to connect DOE funded activities with commercialization opportunities.

Policy and Valuation

1. Identify and assess federal, state, and local policies and regulations with significant impacts on the deployment, operation, and value of both stationary and transportation related energy storage technologies.

2. Develop cutting-edge data, tools, and analyses to address policy and valuation issues and needs.

3. Deliver these products to stakeholders through a coordinated, systematic, and reoccurring engagement program.

4. Ultimately, help stakeholders make informed decisions that maximize the utility and value of energy storage technologies for both the energy system and end users.

Workforce Development

1. Strengthen and broaden the relevance of existing programs through increased stakeholder input across the breadth of the ESGC.

2. Conduct a Needs Assessment/Skills Assessment at all education levels and target audiences and include assessment and evaluation of effectiveness of these programs.

3. Look for opportunities to enhance or develop programs across DOE that will enable the development of the workforce of the future in energy storage at all stages of education and skill sets.

Appendix 1: Technology Development Use Cases

Table 8. Facilitating an evolving grid[59]

Use Case	Facilitating an Evolving Grid
Scope	• The U.S. electric power system[60]
Major Drivers	• Increasing adoption of variable renewable energy and DER deployment • Support utilities, local governments, and states with net-zero emissions or 100% clean energy targets[61] • Dynamic changes in customer demand • Increased resilience in response to weather, physical, and cyber threats[62] • Increased number of microgrid and minigrid installations
Success Criteria	• Cost-effective storage, flexibility, and enabling technology solutions to maintain and enhance the provision of electricity services to end users as the grid increases in complexity and diversity • Reduction of greenhouse gas emissions while maintaining high grid reliability and resilience, as well as low costs to ratepayers • Modular, scalable, and available systems that are safe to install and operate
Beneficiaries	• Ratepayers • Utilities, balancing authorities • Localities, states, regions • Stakeholders managing external threats to the grid • DER operators
Potential Requirements	• Relaxed space constraints • Demonstrated investment-grade performance • Bidirectional capabilities • Black start capable • Longer discharge durations than are economical with current storage technologies. Examples of long duration could range up to 100-150 hours.[63] • Long service lifetime (e.g., 20 years) • Round trip efficiency > 50%
Potential Cost	• Levelized cost of storage of \$0.03-\$0.05/kWh (cost per kwh charged/discharged)

59 Use Case development participants included Max Wei (LBNL, Coordinator), Katrina Krulla (NETL), Avi Shultz (DOE/EERE/SETO), Nathan Weiland (NETL), Anthony Burrell (NREL), Vikram Linga (EIA), Steve Eglash (SLAC), Jaffer Ghouse (NETL), Hayden Reeve (PNNL), Robert Podgorney (INL), Ryan Wiser (LBNL), Andrew Mills (LBNL), Cyndy Wilson (DOE/OP), Tina Kaarsberg (DOE/EERE/AMO), and Tom Tarka (NETL).

60 This Use Case considers system-level effects (i.e., front of the meter) vs. the facility-centric (behind the meter) of Facility Flexibility. For threat and change vectors, this Use Case considers the changes that can be reasonably foreseen (or happen with sufficient frequency to be incorporated into current planning or investment processes), as opposed to the disaster resilience/dependent network infrastructure cases, which deal with vectors that happen too rarely or suddenly to guide investment decisions.

61 Commenters on this driver included Form Energy, EEI, GE, IEEE, Southern Company, Ford, and Siemens.

62 Text from U.S. DOE, "Potential Benefits of High-Power, High-Capacity Batteries," January 2020, https://www.energy.gov/sites/prod/files/2020/02/f71/ Potential_Benefits_of_High_Powered_Batteries_Report.pdf

63 Comments on duration spanned a wide range. This target range reflects recent and anticipated technological and market developments.

Table 9. Serving remote communities[64]

Use Case	Serving Remote Communities
Scope	• Island, coastal, and remote communities
Major Drivers	• Electricity cost premium due to fuel supply logistics and increased maintenance costs • Fuel supply disruptions • Low power quality/reliability • Lack of existing bulk power supply • Cost-effective storage enables on-site renewables such as solar PV • Life safety in harsh environments
Success Criteria	• Clean, resilient, and cost-effective storage and flexibility solutions to provide thermal energy and electricity for critical and beneficial public services

Beneficiaries	• Communities that face the following:
	  ○ Without current electrical infrastructure
	  ○ Have power provided by delivered fuel
	  ○ Bulk power connections are not practical or economically unfeasible
	• Remote federal sites including Department of Defense, National Park Service, and U.S. Forest Service locations
	• Grid-connected communities with low local resiliency and flexibility

Potential Requirements	• Long lifetimes with little maintenance access • Ability to ship to remote locations • Ability to withstand harsh climates • Long duration • Ability to maintain with local workforce (in remote, island, and coastal communities) • Ancillary services to support small grids (black start, frequency response) • Optimization of thermal storage with generator waste heat/excess VRE generation • Safe, presenting low or no safety risks either in operation or in end-of-life disposal/recycling • Ability to tolerate and address wider power, voltage, or frequency deviations compared to typical grid-connected resources
Potential Cost Targets	• Backup generator offset[65] [Delivered Energy Cost Targets: $65/MWh][66] • Avoided cost caused by poor power quality/reliability

[64] Use Case development participants included Michael Ropp (Sandia, co-lead), Hugh Ho (DOE/OP), Steve Bukowski (INL), Andre Pereira (DOE/OE), John Vetrano (DOE/BES), Vincent Sprenkle (PNNL, co-lead), Paul Syers (DOE/EERE/AMO), Richard Tusing (NREL), Eric Miller (DOE/EERE/HFTO), and Michael Starke (ORNL).

[65] https://www.nrel.gov/docs/fy19osti/72509.pdf

[66] Ben A. Wender, "Electricity Use in Rural and Islanded Communities: Summary of a Workshop," 2016, National Academies Press. Value is an average of listed lower and higher bounds for this target.

Table 10. Electrified mobility[67]

Use Case	Electrified Mobility
Scope	• Charging infrastructure, including the distribution grid • Energy storage systems in electric vehicles • Battery recycling and secondary use
Major Drivers	• Fast charging can stress the delivery capacity of the local distribution grid • Leveraging lower costs and improved performance of electric vehicle batteries • Increase of electric vehicle penetration levels and tightening emission standards • Reduction of critical materials use and improving supply chain stability
Success Criteria	• Clean and cost-effective storage solutions that facilitate a large-scale adoption of electric vehicles while maximizing beneficial coordination with the power grid
Beneficiaries	• Fleet owners, including ○ Department of Defense and other agencies with a large fleet ○ Delivery companies, logistics operators ○ Emergency and first responders • Electric utilities • EV consumers • New business models, such as charging station operators • States, localities, or communities with transportation-related emissions targets • Electric vehicle and equipment manufacturers • Transportation hubs (e.g., Port Authority of New York and New Jersey) • Mining, rail, and marine Use Cases
Potential Requirements	• High power (especially for DC fast charging for medium- and heavy-duty vehicles) • Robust buffer storage for distribution grid • New innovative EV batteries with higher energy density and lower cost • Reduction/elimination of critical materials and/or development of low cost domestic sources
Potential Cost Targets	• Demand charge reduction [Storage Cost Targets: $104/kw-yr] [68] • Onboard EV battery costs[69] $80/kWh manufactured cost for a battery pack by 2030[70]

Table 11. Interdependent network infrastructure[71]

Use Case	Interdependent Network Infrastructure
Scope	• Infrastructure sectors critical to electric grid operations, including ○ Natural gas and water ○ Communications, information technology, financial services
Major Drivers	• Interdependencies mean loss of function and service within these infrastructures can have far-reaching costs and impacts • Evolving cybersecurity risks

67 Use Case development participants included Madhu Chinthavali (ORNL, co-coordinator), Seth Snyder (INL, co-coordinator), Michael Starke (ORNL, co-coordinator), Claus Daniel (ORNL), Michael Kintner-Meyer (PNNL), John Farrell (NREL), Ralph Muehleisen (ANL), Sam Baldwin (OE/EERE), Vince Battaglia (LBNL), Vinod Siberry (DOE/OE), Stan Atcitty (SNL),Tien Duong (OE/EERE/VTO), Rima Oueid (DOE/OTT), and Stephen Hendrickson (DOE/OTT).

68 Balducci, 2018. Web. doi:10.1039/C8EE00569A. https://www.osti.gov/pages/biblio/1440273

69 For more information on EV battery cost targets, see https://www.energy.gov/eere/vehicles/batteries

70 https://www.energy.gov/sites/prod/files/2020/08/f77/Boyd-2020_AMR_Plenary-Batteries_and_Electrification_Overview_0.pdf

71 Use Case development participants included Brennen Smith (ORNL, Co-Coordinator), Kunal Thaker (INL, Co-Coordinator), Stewart Cedres (DOE/OE), Sumanjeet Kaur (LBNL), Rolf Butters (DOE/EERE/AMO), and Al Hefner (DOE/EERE/AMO).

Use Case	Interdependent Network Infrastructure
	• Growth of network-connected devices, systems, and services which comprise growing Internet of Things (IoT) in the electrical distribution system[72]
Success Criteria	• Maintain safe and secure infrastructure operations • Cost-effective storage solutions that sustain and enhance normal operations amidst short-term disruptions of energy inputs
Beneficiaries	• Owner-operators of critical infrastructure equipment and systems

Potential Requirements	• Footprint in space-constrained installations
	• ESS used to support gas infrastructure
	  ○ When gas plant ramping is needed during periods of high load and low solar generation (evenings), ESS will take burden off gas infrastructure by providing similar ramping services[73]
	• ESS should have cybersecurity features built into designs that maintain the integrity of the electrical grid's information and communication systems;[74] features include:
	  ○ Secure communications
	  ○ Logging capabilities
	  ○ Secure (validated, signed, and updated) software and firmware
	  ○ Ability to remove/disable unnecessary software, firmware, services, ports, access, hidden accounts, etc.
	• ESS co-located with cell towers need the following performance attributes:[75]
	  ○ Capable of short- and medium-load response
	  ○ Provides sufficient power quality
	  ○ Reliable and scalable
	  ○ Support emerging 5G infrastructure[76]
	  ○ California regulatory requirement: provide backup power of 72 hours during emergencies and electricity shutoffs
	• ESS used in nuclear facilities that can provide power to key critical main control room indications and controls for critical safety system sub-components[77]
	• ESS used for auxiliary power in wastewater and drinking water systems should provide (in accordance with New Jersey best practices):
	  ○ 12 hours of full power backup available during ordinary course of business
	  ○ 72 hours of power backup to maintain effective operations in preparation of forecasted events[78]

Potential Cost Targets	• Power reliability [Storage Cost Targets: $77/kw-yr] [79] • Remote backup generators can cost ~$107/day in O+M costs, installed capital costs of $1000/kWh, and fuel costs ~$3/kWh[80]

72 EEI RFI Response

73 LLNL RFI Response

74 EEI RFI Response

75 Gridtenial Energy RFI Response cites: https://www.cedgreentech.com/customer-project/cell-tower-474-kwh-battery-bank

76 RFI International RFI Response

77 Exelon Nuclear BlackStarTech ™ RFI Response

78 New Jersey Department of Environmental Protection Auxiliary Power Guidance and Best Practices: https://www.nj.gov/dep/watersupply/pdf/guidance-ap.pdf

79 Balducci, 2018. Web. doi:10.1039/C8EE00569A. https://www.osti.gov/pages/biblio/1440273

80 Westell Cell Tower Site Case: http://c.eqcdn.com/_74096f19f51aa39ec811dd24c654f021/westell/db/361/31450/file/Powering+Your+Cell+Towers.pdf

Table 12. Critical services[81]

Use Case	Critical Services
Scope	• Critical sectors, including: ○ U.S. Department of Defense ○ Emergency services ○ Government facilities ○ Healthcare and public health ○ Transportation services (e.g., airports, ports) • Companies, manufacturers who need to maintain operations
Major Drivers	• Need for business or mission continuity given disaster-related and other power outages • Power reliability requirements • Desire to avoid fossil fuels and associated emissions with backup generators • Potential to generate revenue through demand reduction, energy price arbitrage, or participation in ancillary service markets
Success Criteria	• Cost-effective storage, flexibility, and enabling technology solutions that maintain critical services for a sufficient duration following extended power outages
Beneficiaries	• Owners, operators, and users of critical sector facilities • Residents and businesses relying on critical services • Electric utilities, with higher reliability scores as critical customers
Potential Requirements	• Long lifetimes with minimal maintenance requirements • Safety and hazard constraints in sensitive locations • Grid forming capabilities, designed to be islanded • Ancillary services for campus grids (e.g., black start, frequency response) • Interoperability with building/grid management and control systems • Integration with building HVAC / campus thermal systems • Footprint in space-constrained installations • Ability to maintain facility operations for extended hours (e.g., pairing with another generation source such as PV, standby generators, and CHP)
Potential Cost Targets	• Power reliability[82] [Storage Cost Targets: $77/kw-yr] • Backup generator offset[83] [Storage Cost Targets: $1392/kw-yr]

Facility Flexibility, Efficiency, and Value Enhancement

The Facility Flexibility, Efficiency, and Value Enhancement Use Case[84] includes the optimization of processes, behaviors, or value within the boundaries of facilities including utility-scale power generators and electricity consumers (i.e., the non-utility side of a revenue or customer meter). Recognizing the significant differences in the nature and intensity of energy flows both across and within specific energy-relevant sectors, this Use Case considers two specific sub-families, which are covered separately in this section:

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81 Use Case development participants included Cliff Ho (SNL Coordinator), Venkat Srinivasan (ANL), Murali Baggu (NREL), Imre Gyuk (DOE/OE), Scott Litzelman (DOE/ARPA-E), Babu Chalamala (SNL), Adam Weber (LBNL), Travis McLing (INL), and Jun Liu (PNNL).

82 Balducci, 2018. Web. doi:10.1039/C8EE00569A. https://www.osti.gov/pages/biblio/1440273

83 https://www.nrel.gov/docs/fy19osti/72509.pdf

84 Use Case development participants included Jeff Hoffmann (NETL, Coordinator), Susan Babinec (ANL), Joe Cresko (DOE/EERE/AMO), Paul Denholm (NREL), Roderick Jackson (NREL), Robert Kostecki (LBL), Robert Podgorney (INL), Karma Sawyer (DOE/EERE/BTO), Erik Spoerke (Sandia), Michael Starke (ORNL), Paul Syers (DOE/EERE/AMO), Nathan Weiland (NETL), Briggs White (NETL), and Rigel Woodside (NETL).

- Sub-case 1: Flexibility for Commercial and Residential Buildings
- Sub-case 2: Flexibility for Energy-Intensive Facilities (including Electric Power Generation and Industrial Process Applications)

Table 13. Flexibility for commercial and residential buildings

Use Case	Flexibility for Commercial and Residential Buildings
Scope	• Commercial and residential buildings
Major Drivers	• Enhance the overall facility value to the owner, operator, and the occupant • Promote distributed renewable generation use in buildings • Assist in reducing peak demand and high price electricity use when the grid has constrained capacity • Resilience of building operations • Local codes and regulations
Success Criteria	• Behind the meter storage and flexibility solutions that deliver net benefits including energy expenditures, comfort, and functionality • Market penetration of flexible building technologies and energy storage
Beneficiaries	• Commercial and residential building owners, operators, and occupants • Utility and grid operators seeking means to avoid costly grid upgrades • Government agencies wishing to promote reduced carbon emissions, increased renewable energy generation, improve resiliency • Businesses that are experiencing load growth • Lower operating costs for building owners and occupants • Improved productivity and comfort for building occupants • Increased asset value for building owners
Potential Requirements	• Flexibility and optimized management and control of energy demand and generation o The increased ability to control when energy is (dis)charged based on different influencing factors (local climate conditions, user needs, and grid requirements) o Hardware and software upgrades enabling real time assessment of building and grid needs • Measurement and Verification o Methods to analyze and verify the flexible services being provided o Enrollment of equipment in utility program that takes advantage of flexible capabilities o Building thermal management improved utilization - The increased ability to control when thermal energy is (dis)charged and at what temperatures this occurs o Long lifetime - Removal of barriers to long cycle life can lead to significantly improved economics o Low capital costs - Focus on low-cost materials and ways to reduce system complexity and Balance of Plant (BOP) needs o High energy and power density - To reduce the size and cost of storage installations, and increase their efficiency using materials with both high energy and power densities o High roundtrip efficiency (RTE) o Minimum to no fire/explosion/toxicity hazards o Ease of installation - Minimum footprint for space/weight constrained applications - Workforce education o Aligned incentives to encourage building owner adoption o Compliance with building codes

Use Case	Flexibility for Commercial and Residential Buildings
	- Update and revisit on a periodic basis possibly coinciding with ASHRAE and IECC codes ○ Improved characterization techniques of thermal storage media including building thermal mass ○ Storage duration that can be tailored for specific needs of a building, occupant or the grid
Potential Cost Targets	• TOU charge reduction[85] [Storage Cost Targets: $65/kw-yr] • Demand charge reduction[86] [Storage Cost Targets: $104/kw-yr] • Distribution Upgrade Deferral[87] [Storage Cost Targets: $93/kw-yr] • Transmission Upgrade Deferral[88] [Storage Cost Targets: $124/kw-yr] • Energy Arbitrage[89] [Storage Cost Targets: $52/kw-yr] • Weekly/Monthly/Seasonal Storage [Storage Cost Targets: $85/kwh][90] • Power reliability[91] [Storage Cost Targets: $77/kw-yr]

Table 14. Flexibility for energy-intensive facilities

Use Case	Flexibility for Energy-Intensive Facilities
Scope	• Energy-intensive facilities, including ○ Electric power generation ○ Industrial process applications
Major Drivers	• Opportunities for improvement in economics, flexibility, asset utilization, generating capacity, reliability, safety, resiliency,[92] and market diversity. • Sustainable power generation including fuel switching and co-firing (biomass, hydrogen) and carbon mitigation including carbon capture utilization and storage.[93] • Reduce/delay infrastructure investments by flattening load demand curve and improved asset/interconnection utilization. Support grid with ancillary services and rotating equipment provided inertia.
Success Criteria	• Storage and flexibility solutions that maximize the total value obtained from the process of interest • Demonstrations and commercial activity generated
Beneficiaries	• Utility plant owners and operators • Industrial plant owners and operators • Grid operators[94]

85 Balducci, 2018. Web. doi:10.1039/C8EE00569A. https://www.osti.gov/pages/biblio/1440273

86 Balducci, 2018. Web. doi:10.1039/C8EE00569A. https://www.osti.gov/pages/biblio/1440273

87 Balducci, Patrick J., Alam, M. Jan E., Hardy, Trevor D., and Wu, Di. *Assigning value to energy storage systems at multiple points in an electrical grid*. United Kingdom: N. p., 2018. Web. doi:10.1039/C8EE00569A. https://www.osti.gov/pages/biblio/1440273

88 Balducci, 2018. Web. doi:10.1039/C8EE00569A. https://www.osti.gov/pages/biblio/1440273

89 Balducci, 2018. Web. doi:10.1039/C8EE00569A. https://www.osti.gov/pages/biblio/1440273

90 Ziegler, Micah S., et al. "Storage requirements and costs of shaping renewable energy toward grid decarbonization." *Joule* 3.9 (2019): 2134-2153. Midpoint value calculated based off low and high scenarios.

91 Balducci, 2018. Web. doi:10.1039/C8EE00569A. https://www.osti.gov/pages/biblio/1440273

92 Comments from Exelon Nuclear

93 Comments from Enlighten Innovations, Texas A&M, and others

94 Comments from Aestus Energy, Ford Motor Company

Use Case	Flexibility for Energy-Intensive Facilities
Potential Requirements	• Footprint in space-constrained installations[95] • Matching calendar life of the host asset • Ability to match shapes of electricity-intensive industries like aluminum smelting and chlorine production as well as for nuclear, CSP, and fossil power generation.[96] • When incorporated or used in power generation facilities: • Domestically-sourced, cybersecure, energy storage control systems[97] • Rare earth element and critical mineral supply chain security/cost • Facility safety requirements; properly sizing energy storage subsystems for integration with facilities • Realize flexibility benefits, possibly including artificial intelligence approaches leveraging IoT infrastructure • System performance efficiency and charge/discharge rates • Lifetime and degradation rates • Multiple ranges of duration requirements ranging from 1-4 hrs, 3-10 hrs, 12-24 hrs, and shifting energy from weekends to weekdays.
Potential Cost Targets	• Reserves[98] [Storage Cost Targets: $20/kw-yr] • Energy arbitrage[99] [Storage Cost Targets: $52/kw-yr]

95 Comments from Enel Green Power, Ford Motor Company, RTI International, Siemens Energy, Technology Management Applications, and Texas A&M Engineering Experiment Station

96 Comments from OCO, Inc. and SRNL

97 Comments from Exelon Nuclear

98 Balducci, 2018. Web. doi:10.1039/C8EE00569A. https://www.osti.gov/pages/biblio/1440273

99 Balducci, 2018. Web. doi:10.1039/C8EE00569A. https://www.osti.gov/pages/biblio/1440273

Appendix 2: Key Terms

This Appendix lists terms and includes descriptions of the specific connotation/context in which the terms are used in this document.

In this Roadmap, the authors use some terms that can have either different contexts, depending on the industry or scientific field, or definitions that lack the specificity with which they are used. Therefore, we provide specific descriptions of these terms, for clarity to the reader.

1. **Grid service** – when a grid operator remunerates an individual action taken by a generator to provide power or increase the stability and reliability of the electric grid. There are three main types of grid services: capacity, energy, and essential reliability services.[100] Some grid services are currently monetized, while others are not monetized.

    a. **Capacity** – instantaneous power, measured in kilowatts, megawatts, etc.
    b. **Energy** – power generated over a unit of time, measured in kilowatt-hours, megawatt-hours, etc.
    c. **Other grid services** – enable the grid to handle interruptions and power changes over various durations in different locations.
        i. **Operating reserves** – while there is no common definition, the North American Electric Reliability Corporation defines operating reserves as "a capability above firm system demand required to provide for regulation, load forecasting error, equipment forced and scheduled outages, and local area protection."[101]
        ii. **Black start** – capacity that can be started without either external power or a reference grid frequency, and then provide power to start other generators.
        iii. **Voltage control** – used to maintain voltage within tolerance levels and provided by local resources.
2. **System-level** – aspects that have to do with complex interactions between multiple components and sub-systems. System-level challenges or innovations deal with entire energy storage systems, or full operational systems (such as microgrids and hybrid systems) of which an energy storage system is a subsystem. System-level aspects are differentiated from aspects that have to do with individual components.

3. **Energy storage performance goals** – in developing a framework for evaluating the applicability of various energy storage technologies for specific Use Cases, the ESGC has examined the range of various performance aspects needed by the different identified Use Cases and developed a set of performance aimed at addressing these critical performance needs. This set of performance goals serves the purpose of aiding in identifying the specific energy storage technology (or technologies) that is a likely solution for each Use Case. Though many draw from

100 Denholm, Paul, Yinong Sun, and Trieu Mai. 2019. *An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20 72578. https://www.nrel.gov/docs/fy19osti/72578.pdf

101 NERC. 2018. "Glossary of Terms Used in NERC Reliability Standards." https://www.nerc.com/pa/Stand/Glossary%20of%20Terms/Glossary_of_Terms.pdf.

standards and analyses of needs, they are not intended to be major standards themselves. The performance goals, along with metrics defined in that evaluate those goals, are described here:

a. **Load response** – able to respond to frequency needs of the grid or user. There are three classifications of load response:
    i. **Short-duration** – able to respond to frequency needs of the grid or user (frequency regulation, frequency response, etc.)
    ii. **Mid-duration** – able to respond to shifting capacity needs of the grid or user over the course of a few (1–18) hours (load shifting, arbitrage, spinning/non-spinning reserves, transmission congestion relief, etc.)
    iii. **Long-duration** – able to provide services over several days or weeks to meet needs of grid or user (energy and operating reserves, long-term buybacks, resilient VRE integration, etc.)
    iv. Performance metrics, defined in Appendix 5, that assess progress towards this goal include *Duration*, *Response Time Constrained by Power Conversion Systems*, and *Theoretical Response Time*.
b. **Black start capable** – can provide other systems with the initial power input required for them to start up, usually after a black-out (also known as “Grid Forming”).
c. **Power quality** – provides smooth electricity supply without variations in voltage, frequency, harmonics, unexpected interruptions of any duration, etc.
    i. Performance metrics, defined in Appendix 5, that assess progress towards this goal include *Discharge Voltage Variability*.
d. **Reliable** – can provide power, even after long inactive periods.
    i. Performance metrics, defined in Appendix 5, that assess progress towards this goal include *Calendar Life*.
e. **Robust** – able to withstand extreme use conditions (mechanical distress, cold temperatures, extreme weather) and not fail.
    i. Performance metrics, defined in Appendix 5, that assess progress towards this goal include *Maximum Operating Temperature* and *Minimum Operating Temperature*.
f. **Scalable** – possible to cost-effectively build large-scale (MW) systems.
    i. Assessing progress towards this goal would involve comparing how cost metrics (defined in Appendix 5) associated with energy ($/kWh) or power ($/kW) change with system size. Systems with a lower (or more negative) size to cost metric correlation would be more scalable.
    ii. **Long lifetime** – able to perform (e.g., <20%) capacity degradation. Often used in the context of extending storage lifetimes to match renewable power purchase agreement terms. Performance metrics, defined in Appendix 5, that assess progress towards this goal include *Operational Life*, *Cycle Life*, *Cycles Per Day*, *Cycles Per Year*, and *Degradation Factor*.
g. **Compact** – has the energy density and total system characteristics to cost effectively meet requirements for systems with size and weight restrictions (AVs, UAVs, mobile stationary units, etc.).
    i. Performance metrics, defined in Appendix 5, that assess progress towards this goal include *Energy Density*, *Footprint*, *Power Density*, and *Weight*.
h. **Safe** – presents low or no safety risks either in operation or in end-of-life disposal/recycling.

    i. Performance metrics, defined in Appendix 5, that assess progress towards this goal include *Limited Oxygen Index*, *% Environmentally-Sensitive Material*, *Recyclability*, and *Self-Extinguishing Time*.

i. **Efficient** – achieves a high enough conversion efficiency to cost-effectively integrate with necessary energy sources.

    i. Performance metrics, defined in Appendix 5, that assess progress towards this goal include *Ramp Rate* and *Round Trip Efficiency*.

j. **Flexible**[102] – able to easily integrate and operate with existing generation systems and infrastructure.

k. **Modular**[103] – can be configured to easily combine with other storage systems to achieve precise capacity targets (“plug-n-play”).

[102] Enel Green Power, Energy Vault, Form Energy Inc, GE Research, IEEE, Redstone Technology Integration RFI Responses

[103] ABB Inc., Enel Green Power, Energy Vault, Form Energy Inc, GE Research, IEEE RFI Responses

Appendix 3: Energy Storage Technologies and DOE Activities

Introduction

DOE is undertaking a range of R&D activities to increase the ability of energy storage technologies to provide higher power and longer duration capabilities. Not every storage or battery technology is represented in the following sections. This summary focuses on technologies that are currently being deployed or are active research areas within the DOE program offices. DOE research in energy storage is coordinated by federal staff participation in cross-DOE program and proposal reviews, advisory committee meetings, responses to congressional requests, and regular meetings that include office leadership. In the President's Fiscal Year 2021 budget request, DOE included the ESGC, which seeks to establish stronger cross-office activities and shared technology targets.

This Appendix is based on Appendix B of the report to Congress on the "Potential Benefits of High-Power, High-Capacity Batteries."[104]

[104] https://energy.gov/sites/prod/files/2020/02/f71/Potential_Benefits_of_High_Powered_Batteries_Report.pdf

Table 15. DOE storage activity overview by technology, stage, and DOE office

<table>
<tr><th colspan="3">Fundamental R&D (F)
Applied R&D (A)
Manufacturing R&D (M)
Commercialization (C)</th><th>Materials</th><th>Components & Devices</th><th>System Design (Bal. of Plant)</th><th>System Integration</th><th>Investment/ Finance</th><th>Operations</th><th>Markets/ Value</th><th>End of Life</th></tr>
<tr><td rowspan="14">Bidirectional Electrical Storage</td><td rowspan="8">Electrochemical</td><td>Li-ion</td><td>SC(F)
VTO(FAM)
AMO(AM)
ARPA-E(A)</td><td>VTO(FAM)
ARPA-E(A)</td><td>VTO(A)
ARPA-E(A)</td><td rowspan="5">VTO(AMC)
OE(AC)</td><td rowspan="5">VTO(C)
OE(C)
LPO(C)</td><td rowspan="5">VTO(A)
OE(A)
SETO(A)</td><td rowspan="8">VTO(A)
OE(AC)
ARPA-E(A)
SETO(AC)</td><td>VTO(FAM)
OE(A)
AMO(FAM)</td></tr>
<tr><td>Na-ion & Na Metal</td><td>SC(F)
VTO(FA)
OE(A)</td><td>VTO(FA)
OE(A)</td><td>VTO(A)
OE(A)</td><td>OE(A)</td></tr>
<tr><td>Lead Acid</td><td>OE(A)</td><td>OE(A)</td><td>OE(A)</td><td>OE(A)</td></tr>
<tr><td>Zinc</td><td>SC(F)
OE(A)</td><td>OE(A),
ARPA-E(A)</td><td>OE(A)
ARPA-E(A)</td><td>-</td></tr>
<tr><td>Other Metals (Mg, Al)</td><td>SC(F)</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Redox Flow</td><td>SC(F)
ARPA-E(A)
AMO(M)</td><td>ARPA-E(A)</td><td>OE(AC)</td><td>OE(C)
LPO(C)
FE(A)</td><td>OE(A)
LPO(C)</td><td>OE(A)</td><td>-</td></tr>
<tr><td>Reversible Fuel Cells</td><td>HFTO(FAM)
FE(A)</td><td>HFTO(AM)
FE(A)</td><td>HFTO(AM)
FE(A)</td><td>HFTO (AMC)
FE(A)</td><td>-</td><td>-</td><td>OE(A)
HFTO(FAM)</td></tr>
<tr><td>Electro-chemical Capacitors</td><td>SC(F)</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td rowspan="6">Electromechanical</td><td>Pumped Hydro</td><td>WPTO(AM)</td><td>WPTO(A)</td><td>WPTO(A)</td><td rowspan="6">WPTO(A)
OE(A)
FE(A)</td><td rowspan="6">WPTO(A)
OE(A)
LPO(C)</td><td rowspan="6">WPTO(A)
OE(A)</td><td rowspan="6">WPTO(A)
OE(AC)
ARPA-E(A)</td><td>-</td></tr>
<tr><td>Compressed Air</td><td>-</td><td>OE(A)</td><td>OE(A)</td><td>-</td></tr>
<tr><td>Liquid Air</td><td>-</td><td>-</td><td>FE(A)</td><td>-</td></tr>
<tr><td>Flywheels</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Geomechanical</td><td>ARPA-E(A)</td><td>ARPA-E(A)</td><td>ARPA-E(A)</td><td>-</td></tr>
<tr><td>Gravitational</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
</table>

Fundamental R&D (F) Applied R&D (A) Manufacturing R&D (M) Commercialization (C)			Materials	Components & Devices	System Design (Bal. of Plant)	System Integration	Investment/ Finance	Operations	Markets/ Value	End of Life
Thermal & Chemical	Thermal	High-Temperature Sensible Heat	ARPA-E(A) SETO(AMC) AMO(M) FE(AMC)	ARPA-E(A) SETO(AMC)	SETO(AC) FE(A)	ARPA-E(A) SETO(A) FE(A)	-	FE(A)	OE(AC) ARPA-E (A) SETO(AC) FE(AC)	-
		Phase Change	BTO(AMC) SETO(AC)	SETO(AMC) FE(A)	SETO(AC)	SETO(AC)	-	-		-
		Low-Temperature Storage		GTO(A)	GTO(A)	-	-	-		-
		Thermo-photovoltaic	ARPA-E(A) SC (F)	ARPA-E(A)	ARPA-E(A)	-	-	-		-
		Thermochemical	ARPA-E(A) SETO(AC)	ARPA-E(A) SETO (AMC)	ARPA-E(A) SETO(AC)	SETO(AC)	-	-		-
	Chemical	Chemical Carriers (e.g., Ammonia)	HFTO(A) ARPA-E(A) SETO(A) FE(A)	HFTO(A) ARPA-E(A) FE(A)	HFTO(AM) ARPA-E(A) SETO(A) FE(A)	HFTO(AM) ARPA-E(A) FE(A)	-	FE(A)	OE(AC) ARPA-E (A) SETO(AC) FE(AC)	-
		Hydrogen	SC(F) HFTO(FAM) ARPA-E(A) SETO(A) FE(A)	HFTO(AM) ARPA-E(A) FE(A)	HFTO(AM) ARPA-E(A) FE(A)	HFTO(AMC) SETO(A) FE(A) NE(A) LPO(C)	LPO (C)	HFTO(A) FE(A)		HFTO (FAM)
Flexible Generation & Loads	Flexible Buildings	Thermostatically Controlled Loads	BTO(AM)	-	-	-	-	-	OE(AC) ARPA-E(A) SETO (AC) WPTO(A)	-
		Building Mass	BTO(AM)	BTO(A)	BTO(A)	-	-	-	-	-
		Ice and Chilled Water	BTO(A)	BTO(A)	-	-	-	-	-	-

Fundamental R&D (F) Applied R&D (A) Manufacturing R&D (M) Commercialization (C)			Materials	Components & Devices	System Design (Bal. of Plant)	System Integration	Investment/ Finance	Operations	Markets/ Value	End of Life
		Organic Phase Change Material[105]	BTO(A)	BTO(A)	-	-	-	-	-	-
		Salt Hydrate[106]	BTO(A)	BTO(A)	-	-	-	-	-	-
		Thermochemical[107]	BTO(A)	BTO(A)	-	-	-	-	-	-
		Desiccant	BTO(A)	BTO(A)	BTO(A)	-	-	-	-	-
	Flexible Generation	Ramping	FE(C)	FE(C)	FE(C)	SETO(A) WETO(A) FE(A)	-	SETO(A) WETO(A) FE(AC)	-	-
	Flexible Generation	Behind-the-Meter Generation plus Storage	-	GTO(A)	WPTO(A), GTO(FA)	SETO(A) WPTO(A) WETO(A)	WPTO(A)	SETO(A) WPTO(A) WETO(A)	-	-
Crosscutting	Power Electronics	Power Electronic Systems	SC(F) AMO(AM) ARPA-E(A)	VTO(FA) AMO(AMC) ARPA-E(A) SETO(AMC) OE(FA)	VTO(A) ARPA-E(A) SETO(AC) WETO(A) OE(A)	VTO(A) AMO(A) SETO(A) OE(A)	-	-	SETO(A)	OE(AC) ARPA-E(A) SETO(A)

DOE abbreviations included in table: ARPA-E: Advanced Research Projects Agency–Energy, AMO: Advanced Manufacturing Office, BTO: Building Technologies Office, FE: Office of Fossil Energy, GTO: Geothermal Technologies Office, HFTO: Hydrogen and Fuel Cell Technologies Office, OE: Office of Electricity, SETO: Solar Energy Technologies Office, LPO: Loan Programs Office, SC: Office of Science, VTO: Vehicle Technologies Office, WETO: Wind Energy Technologies Office, WPTO: Water Power Technologies Office

105 This would also be considered a thermal technology but given the considerable amount of research activities that examine this technology in facility related applications, the ESGC classifies these under the Flexible and Controllable Loads section.

106 This would also be considered a thermal technology but given the considerable amount of research activities that examine this technology in facility related applications, the ESGC classifies these under the Flexible and Controllable Loads section.

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Bidirectional Electrical Storage

Bidirectional electrical storage includes technologies and systems that are capable of absorbing electric energy, storing that energy for a period of time, and dispatching the stored energy in the form of electricity. They include the following classes of technologies: electrochemical, mechanical, and electrical storage. Electrochemical storage systems use chemical reactions to convert and store energy, encompassing a range of battery chemistries and designs as well as reversible fuel cells for stationary and transportation applications. Mechanical storage systems use mechanical methods to convert and store electrical energy. These systems include pumped water, compressed air, spinning flywheels, and emerging gravity storage systems. Electrical storage systems store electrical energy directly using specialized materials include capacitors and superconducting magnetic coils. Thermal and chemical energy storage systems can also be used for bidirectional electrical storage by using electricity to charge the thermal or chemical reservoir and discharging, on demand, through a heat engine, fuel cell, or other power conversion device.

Electrochemical

Lithium-ion Batteries

Ability to Provide Functional Requirements

Lithium-ion batteries are one of the most widely used technologies for portable electronics due to their high energy density and cycling performance. These systems store electrical energy in electrodes that can accommodate lithium within their atomic structure, called intercalation or insertion compounds. Most commercial lithium-ion batteries generally comprise a graphite anode, a lithium-containing transition metal oxide or phosphate cathode, and a non-aqueous lithium-ion conducting liquid electrolyte. When using a graphite anode, cells are often characterized by the different cathode materials used (e.g., $LiCoO_2$, $LiNi_xMn_yCo_zO_2$, $LiNi_xCo_yAl_zO_2$, or $LiFePO_4$). On charging, Li^+ ions are removed from the cathode, transferred across the electrolyte, and intercalated between the graphite layers in the anode. The reverse of this process discharges the battery and enables electrical flow when connected to an external circuit. In 2008, one of the first utility-connected lithium-ion storage systems[108] was installed to provide frequency regulation services. Early grid-connected systems focused on higher power (~10 MW) and shorter discharge durations (<1 hour) that made them an ideal solution for frequency regulation and other services that required a fast injection of power over a shorter period of time.

Today's Technology Maturity Level

Early deployments to serve the frequency regulation markets in PJM (the electricity balancing authority for Pennsylvania, New Jersey, and Maryland) had discharge durations as short as 15 minutes. Further reductions in battery costs have enabled longer duration systems to be economically deployed. In response to the Aliso Canyon gas leak in 2016, 70 MW of lithium-ion energy storage systems were deployed, all with 4-hour discharge durations.[109] Currently the largest (by power rating) lithium-ion grid-

108 AES Innovation History. http://innovation.aes.com/innovation-history/default.aspx

109 "Tesla, Greensmith, AES Deploy Aliso Canyon Battery Storage in Record Time," January 2017. https://www.greentechmedia.com/articles/read/aliso-canyon-emergency-batteries-officially-up-and-running-from-tesla-green

scale storage system was installed by Tesla in November 2017 in Hornsdale, Australia. The 100 MW/129 MWh storage system is paired with a 315 MW wind farm.[110]

Constraints on Architecture

The power capability of a lithium-ion cell, or any battery chemistry, is inversely proportional to the resistance within the cell components to the transport of charged lithium ions between the two electrodes. Energy capacity is limited by the amount of accessible electrode materials. Higher power, short-duration cells typically have thinner electrodes, whereas longer duration systems require more material (thicker electrodes) that are often difficult to fully utilize. Because of the inherent high energy density of lithium-ion cells, typical form factors for individual cells are designed with a high surface-area-to-thickness ratio to ensure adequate dissipation of heat. Excessive heat generation accelerated the aging of the cell and can lead to breakdown of the organic electrolyte into flammable gaseous components that may combust in certain conditions. Modules comprised of racks of individual cells are designed to maximize heat dissipation from the cells while reducing the potential of fire propagating from one cell to another. Future technology drivers for EVs and consumer electronics will continue to push for higher energy densities, indicating that future form factors will likely remain constrained by the need to dissipate the heat generated during the charge/discharge cycle. This architectural constraint will require MW scale grid systems to be composed of hundreds of thousands of individual cells, potentially limiting future cost reductions for complete systems due to the need to individually connect each small cell. An architecture based on higher capacity battery cells would address these constraints.

DOE Activity

The DOE Office of Energy Efficiency and Renewable Energy’s Vehicle Technologies Office has played a critical role in advancing the state of battery technologies for EV applications. Early research by the Department led to the nickel-metal-hydride batteries used in the first-generation EVs. In the past decade, the program’s battery development efforts have focused on early stage materials and cell architectures that can significantly reduce cost of lithium-ion systems. In 2019, battery pack costs based on usable energy declined to $185/kWh from over $1000/kWh in 2008 due, in part, to strong DOE investments. VTO is working on several new generations of lithium-ion technology (e.g., silicone anodes, solid state electrolytes, lithium metal) to achieve <$100/kWh by 2028, with an ultimate goal of $80/kWh. This will allow EVs to reach cost competitiveness with future IC engine vehicles.

Today, R&D programs like the Battery500 Consortium[111] are developing the next generation of lithium-based batteries that use a metallic-lithium anode to increase the energy density of a cell to allow for longer duration operation for the same weight of batteries.[112] While significant technology challenges remain, the Battery500 Consortium, if successful, could enable batteries with twice the energy per weight at a cost of <$100/kWh.

Additional R&D efforts by the program are evaluating the impacts of an EV fast-charging infrastructure on battery chemistries and grid stability and how lithium-ion systems can be recycled after their useful

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110 “South Australia’s Tesla battery on track to make back a third of cost in a year,” September 2018. https://www.theguardian.com/technology/2018/sep/27/south-australias-tesla-battery-on-track-to-make-back-a-third-of-cost-in-a-year/

111 https://energystorage.pnnl.gov/battery500.asp

112 https://www.energy.gov/technologytransitions/articles/battery500-consortium-spark-ev-innovations-pacific-northwest-national

life to reduce long-term environmental impacts and supply chain constraints. For lithium-ion batteries, the most pressing supply chain risk is cobalt. The Vehicle Technologies Office has established the ReCell R&D Center and the Battery Recycling Prize to maximize recycling value from end-of-life batteries by recovering cathode and anode material. The Battery Recycling Prize, a jointly funded effort with the Vehicle Technologies Program and the Advanced Manufacturing Office, targets recovering 90% of lithium-ion batteries at their end of life. More information on these battery programs can be found at https://www.energy.gov/eere/vehicles/batteries.

The DOE Office of Electricity's Energy Storage Program is leading efforts to understand the reliability, safety, and use of lithium-ion technologies deployed in the field. With the primary market for technologies focused on non-grid applications, the Office of Electricity is actively developing the knowledge base on how this technology performs under actual and simulated grid duty cycles. DOE supports field demonstrations of lithium-ion technology with state and regional stakeholders to assess the optimal use and economic potential under local operating conditions to better inform large-scale planning models. The program also conducts R&D to determine the expected lifetime of the different lithium-ion chemistries (and other technologies) under various grid duty cycles to give potential storage owners a greater level of confidence in the technology. Finally, the program is actively engaged in understanding the safety and operation of energy storage systems through its Energy Storage Safety Collaborative.[113] The Collaborative works with a broad group of stakeholders—from academia, R&D, codes officials, and first responders—to understand risks and mitigate the frequency and severity of potential incidents. Additional information on the Energy Storage Program can be found at https://www.energy.gov/oe/activities/technology-development/energy-storage with additional technical details at https://www.sandia.gov/ess-ssl/. Along with these R&D activities to better define the safety and reliability of lithium-ion technologies, DOE also conducts R&D on advanced power electronics to lower the cost and improve reliability of converting the DC of the battery to the AC of the grid.

In addition to these efforts, both the Office of Electricity and Vehicle Technologies Office are supporting early stage research into replacing the traditional materials in lithium-ion technologies with the more abundant sodium technologies while retaining the lithium-ion manufacturing process. The rising cost of lithium and supply chain concerns have prompted research into alternative materials that can be substituted for lithium in traditional lithium-ion batteries. Sodium—as the sixth most abundant element in the earth's crust—is readily available and possess a similar chemistry to lithium that favors quick adaptability to the current manufacturing infrastructure. Because sodium-ion is relatively heavier, energy densities are lower than lithium-ion, which limits their potential market to applications that are less sensitive to high energy densities. Commercialization of sodium-ion technology is in the early stages, with a few companies overcoming some of the challenges of cell design and electrode balancing to develop pilot demonstrations. Continued research within several DOE offices is focused on identifying materials and cell chemistries that can enable sodium-based systems to have comparable energy density and life cycle performance to today's lithium-ion while eliminating the cost and supply chain constraints of lithium.

The Office of Basic Energy Sciences (BES) is supporting basic research in materials and chemistry that underpin lithium-ion and lithium-metal battery chemistries such as the lithium-sulfur system being

113 DOE Energy Storage Safety Collaborative. https://www.sandia.gov/energystoragesafety-ssl/

further developed in the Battery500 program referenced above. Through coordination with the Vehicle Technologies Office and ARPA-E, several battery electrodes and electrolytes first studied under BES funding have been translated to commercial products for EVs and grid use.

Sodium-Metal-Based Batteries

Ability to Provide Functional Requirements

The sodium-ion technology mentioned above substitutes sodium-based compounds for lithium and does not require substantive changes to the lithium-ion manufacturing process. Battery technologies such as sodium-sulfur and sodium-metal-halide (or Zebra) batteries, however, use a molten-sodium anode and thus require significantly different cell architectures to function. Both sodium-sulfur and sodium-metal-halide technologies have achieved commercial deployment on the grid, with sodium-sulfur technology being the dominant sodium-metal-based energy storage solution. Both technologies use a solid ceramic electrolyte to transfer charge between a molten-sodium anode and a sulfur (sodium-sulfur) or metal-halide (sodium-metal-halide) cathode. Because the ceramic electrolyte has poor conductivity at room temperature and is necessary for keeping electrode materials in the molten state, these systems typically operate around 300–350˚C, requiring additional insulation and protection. As an analogue to a sodium-sulfur battery, sodium-metal-halide batteries use a transition metal halide (e.g., $NiCl_2$) as the cathode material instead of sulfur and operate at around 280°C. In addition to the ceramic electrolyte, sodium-metal-halide batteries also require a secondary molten salt electrolyte to facilitate charge transport in the cathode. Because of the use of the relatively expensive nickel as the cathode, the cost of sodium-metal-halide batteries is typically higher than for sodium-sulfur batteries.

Today's Technology Maturity Level

Sodium-sulfur batteries, developed by Ford in the 1970s and commercialized in Japan, were the most prevalent grid-scale battery system until the recent rise of lithium-ion technologies. Sodium-sulfur battery technology is typically characterized by longer discharge durations (6–8 hours), high energy density (~150 Wh/kg), and long cycle life (4000 cycles). Sodium-metal-halide batteries have been developed with discharge durations of up to 4 hours and have relatively high energy density (~100 Wh/kg) and long cycle life (3000 cycles). Vendor options for both technologies are limited, with a single commercial vendor of MW-scale sodium-sulfur battery systems existing today. Other companies are producing storage solutions based on sodium-metal-halide technology in the 5–150 kW range or have abandoned technology development since 2015 to focus on lithium-ion technologies.

Constraints on Architecture

Because a higher operating temperature is required to keep the sodium anode and cathode materials in a molten state, high-temperature sodium battery systems require additional precautions to ensure the sodium metal does not violently react if exposed to an oxidant. In sodium-metal-halide technology, the molten secondary electrolyte in the cathode provides additional protection by reducing when exposed to molten sodium and suppressing thermal runaway during failure. The higher temperature operation of these systems places additional constraints on the technology: they must be operated routinely or the parasitic losses to keep the system at temperature can overwhelm any economic benefits. However, the higher temperature and system operations required to remain at temperature make the technologies insensitive to extreme temperature conditions that can impact battery chemistries designed to operate around normal ambient conditions.

DOE Activity

R&D supported by the DOE Office of Electricity's Energy Storage Program is working to address some of the technical barriers limiting the current development of molten sodium-based battery technologies. Because of their high operating temperature, traditional sodium batteries require higher cost materials and manufacturing processes. Research efforts at DOE's National Laboratories are working on novel metal-halide-based chemistries and designs that operate between 150–200˚C. This lower temperature operation enables using lower-cost materials and mass-producible manufacturing processes. Additionally, lowering the operating temperature has also been shown to increase the operational life of these technologies compared to current technologies.

Lead-Acid Batteries

Ability to Provide Functional Requirements

All lead-acid designs share the same basic chemistry: a lead-dioxide positive electrode, a metallic-lead negative electrode, and sulfuric-acid-based electrolyte. Traditional lead-acid batteries for motive application lack the discharge duration for grid-scale storage, but several advancements in the technology have enabled their usefulness for storage applications. Advanced lead-acid technologies typically employ carbon additions to anodes to improve performance and lifetime.

Today's Technology Maturity Level

Invented in 1859, lead-acid batteries are the oldest form of rechargeable battery technology, with wide application as engine starters and industrial backup. An analysis of the rechargeable battery market share by Avicenne Energy (Figure 12 shows the dominance of lead-acid technology in the overall rechargeable battery market).[114]

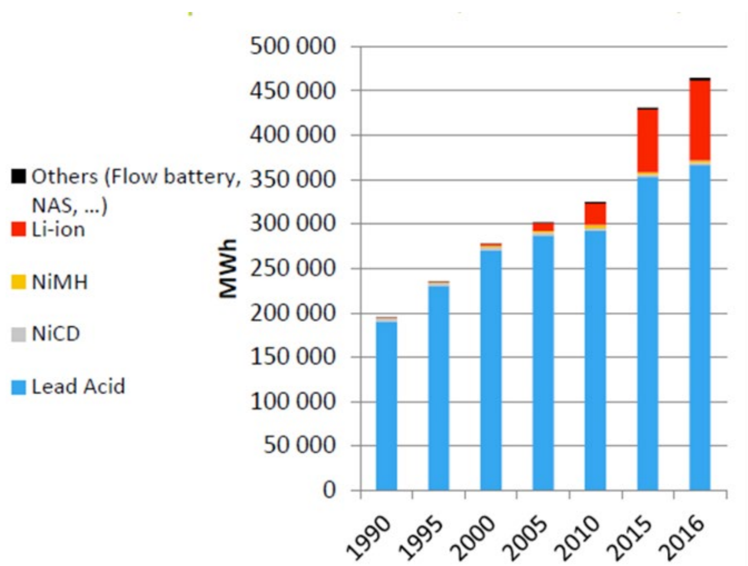

Figure 12. Rechargeable battery market share

114 "Lithium-ion Battery Raw Material Supply and Demand 2016-2025," presented June 2017. http://www.avicenne.com/pdf/Lithium-Ion%20Battery%20Raw%20Material%20Supply%20and%20Demand%202016-2025%20C.%20Pillot%20-%20M.%20Sanders%20Presentation%20at%20AABC-US%20San%20Francisco%20June%202017.pdf

One of the earliest MW-scale energy storage systems deployed on the grid (installed in 1997) was based on lead-acid technology, but recent growth in stationary deployments has centered on UPS systems for telecommunications and backup power applications.

Constraints on Architecture

The design and architecture of lead-acid batteries is very mature. Inherently, lead-acid technologies are low energy density (~30 Wh/l), containing about tenfold less energy by volume than lithium-ion technologies. Overall, capital costs for lead-acid systems are one of the lowest on a $/kWh basis; however, these systems typically use a smaller range of their available capacity (e.g., 30%–70% state of charge compared to 5%–95% for lithium-ion), which increases the cycle life of the technology but also increases the levelized cost by requiring more batteries for a given power and energy output. Current recycling rates for lead-acid batteries are >99% in the United States[115] due to the high lead content contained in the battery (65% lead by weight) and environmental regulations.[116]

DOE Activity

Given the maturity of lead-acid technology DOE has limited R&D programs. As with other technologies, DOE is investigating the impact of typical grid duty cycles on the lifetime and performance of these systems to better inform the technology development process.

Redox-Flow Batteries

Ability to Provide Functional Requirements

A redox-flow battery (RFB), as schematically shown in , is a unique type of rechargeable battery architecture in which the electrochemical energy is typically stored in two soluble redox couples contained in external electrolyte tanks.[117]

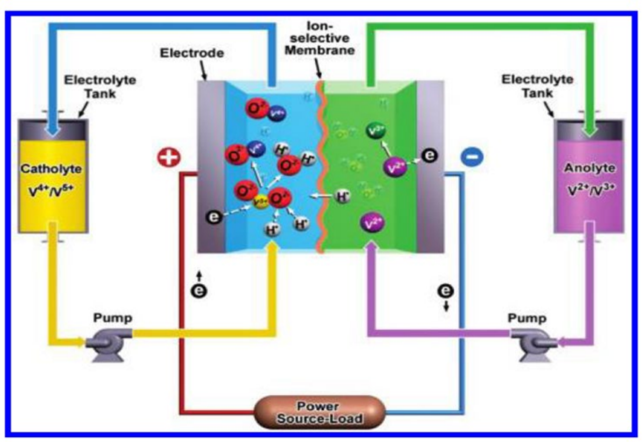

Figure 13. Schematic of an all-vanadium RFB as an example of RFBs (or regenerative fuel cells)[118,119]

115 "Study finds nearly 100 percent recycling rate for lead batteries," November 2017. https://www.recyclingtoday.com/article/battery-council-international-lead-battery-recycling/

116 G.J. May, et al. "Lead batteries for utility energy storage: A review," *Journal of Energy Storage 15* (2018) p.155.

117 Z. Yang, et al. "Electrochemical Energy Storage for Green Grid," *Chem. Rev*. 2011, 111, p 3577–3613.

118 Yang, et. al. *Chem. Rev*. 2011, 111, p. 3683.

119 Z. Yang, et al. "Electrochemical Energy Storage for Green Grid," *Chem. Rev*. 2011, 111, p 3577–3613.

Liquid electrolytes are pumped from the storage tanks through electrodes where the chemical energy in the electrolyte is converted to electrical energy (discharge) or vice versa (charge). The electrolytes flowing through the cathode and anode are often different and referred to as anolyte and catholyte, respectively. Between the anode and cathode compartments is a membrane (or separator) that selectively allows cross-transport of a charge-carrying species (e.g., H^+, Cl^-) to maintain electrical neutrality and electrolyte balance. In traditional battery designs like lithium-ion, the stored energy is directly related to the amount of electrode material and increasing the power capacity of these systems also increases the energy capacity as more cells are added. In redox-flow systems the power and energy capacity can be designed separately. The power (kW) of the system is determined by the size of the electrodes and the number of cells in a stack, whereas the energy storage capacity (kWh) is determined by the concentration and volume of the electrolyte. Both energy and power can be easily adjusted for storage from a few hours to days, depending on the application. This flexibility makes RFBs an attractive technology for grid-scale applications where both high-power and high-energy services are being provided by the same storage system. The basic RFB design is also flexible in the chemistries it can accommodate. Any multivalent element that can be dissolved in a solution can potentially be used in RFB design.

Today's Technology Maturity Level

To date, vanadium-based and hybrid zinc-bromine flow batteries have achieved the most commercial success, with other technologies based on iron-chrome and polysulfide-bromine having been demonstrated but falling short of commercialization. Vanadium flow batteries use the ability of vanadium to exist in four distinct electrically charged species to serve as both the anolyte and catholyte, limiting the impact of species crossover on battery performance. The technology was first demonstrated in the 1980s by Maria Skyllas-Kazacos at the University of New South Wales, with various generations of the technology having attempted field demonstrations and commercialization. In the past decade, the technology has re-emerged as a candidate for grid-scale storage applications due to its long cycle life and effective use of available state-of-charge range. Replacing the flowing anolyte with a metal electrode (e.g., zinc in $Zn\text{-}Br_2$ and iron in Fe/Fe^{2+} technologies) increases the number of chemistries available for use, but also couples the power and energy reducing the operational flexibility. Zinc-based hybrid flow batteries are one of the more promising systems for medium- to large-scale energy storage applications, with advantages in safety, cost, cell voltage, and energy density. Zinc-hybrid systems have the highest energy content due to the high solubility of zinc ions (>10 M) and the solid negative electrode.[120]

Constraints on Architecture

Traditional flow battery technologies, like vanadium flow batteries, consist of a collection of serially connected cells arranged in a stack where the electrochemical reactions occur in external storage tanks containing anolyte and catholyte. This decoupling of power and energy creates a great deal of flexibility in the design architecture, as the size of the stack (relating to flow battery power) and tanks (the energy content of flow batteries) can be independently adjusted depending on the application. Individual cells in a stack can approach a square meter in active area and typically operate at ~1.0 V to prevent hydrolysis of the aqueous solution. Because of this architecture, flow batteries typically provide lower voltage and higher currents to the DC-AC inverter, the reverse of what is delivered by lithium-ion

120 Li B, Z Nie, M Vijayakumar, G Li, J Liu, VL Sprenkle, W Wang. "Ambipolar zinc-polyiodide electrolyte for a high-energy density aqueous redox flow battery," *Nature Communications 6* article number 6303, February 2015.

systems. In addition, most flow battery components are comprised of polymer materials that can be manufactured by traditional molding processes that greatly reduce the cost of production.

DOE Activity

While vanadium flow batteries have achieved initial commercial deployment, further R&D efforts would push the technology to lower cost. Efforts by the DOE Office of Electricity to increase performance and reduce the cost of advanced systems demonstrated that the technology may be able to achieve costs <$300/kWh when deployed at scale.[121] However, the analysis shows that greater than 50% of the cost of a vanadium flow battery system (including the balance of plant and power electronics) is contained within the cost of the vanadium raw materials.[122] Future capital cost reductions will require replacing vanadium with lower cost raw materials to approach the $100/kWh targets required for wider-scale deployment of energy storage.

One approach being developed by the DOE Office of Electricity Energy Storage Program is to replace vanadium with lower-cost, easy-to-synthesize, redox-active organic molecules. A critical design aspect is ensuring these organic redox systems use existing RFB manufacturing capabilities necessitating that new technologies are water soluble with similar concentrations, viscosities, and performance to today's RFBs. Designing these new organic systems to be soluble in water—called aqueous soluble organics—not only ensures these systems are compatible with existing RFB infrastructure but also provide inherent fire safety. Recent research efforts identified a phenazine-based anolyte that offers significant potential for lower cost while demonstrating equivalent performance to state-of-the-art vanadium systems.[123] Additional research will be required to demonstrate the technology is suitable for scale-up and field applications.

ARPA-E, through several energy storage-based solicitations such as the GRIDS, IONICS, and OPEN programs, has supported several high-risk but transformational flow battery technologies. Technologies based on iron, organics, zinc, and lithium slurries have been moved to greater commercial viability by enabling multi-kW scale prototypes to be demonstrated. Recently, ARPA-E awarded four new flow battery projects under its Duration Addition to electricitY Storage (DAYS) program. DAYS focused on economically extending the discharge capacity of flow batteries into the 10- to 100-hour range via means such as reducing the capital cost of the flow battery stack and enabling inexpensive active materials such as sulfur and manganese with low crossover through the central membrane.[124]

FE is supporting a pre-FEED study of a 50 MW vanadium flow battery integrated with an advanced coal power plant equipped with carbon capture and storage under its Coal FIRST program. If meritorious, this study could lead to a future large-scale engineering prototype test.

The Office of Science also supports basic research in electrical energy storage applicable to both transportation and grid storage technologies like flow batteries. The strategic directions are currently

[121] Pacific Northwest National Laboratory, "High Current Density Redox Flow Batteries for Stationary Electrical Energy Storage," PNNL-23819-4, September 2016. https://energystorage.pnnl.gov/pdf/PNNL-23819-4.pdf

[122] Next Generation Redox Flow Battery Development at PNNL. https://www.sandia.gov/ess-ssl/docs/pr_conferences/2015/EESAT%202%20Wednesday/Sprenkle.pdf

[123] A. Hollas, et al., "A biomimetic high-capacity phenazine-based anolyte for aqueous organic redox flow batteries," *Nature Energy* 3, p. 508.

[124] U.S. Department of Energy Advanced Research Projects Agency–Energy, "GRIDS Program Overview." https://arpa-e.energy.gov/sites/default/files/documents/files/GRIDS_ProgramOverview.pdf

driven by the report from the 2017 Basic Research Needs for Next-Generation Electrical Energy Storage Workshop.[125] This workshop included engagement from the DOE energy technology offices with participation from the broad academic, National Laboratory, and industrial research communities. The research priorities focus on fundamental science underpinning batteries for grid energy storage and transportation, such as using advanced synthesis to tailor structures, tuning functionality of materials and chemistry, reducing detrimental chemistries that degrade performance, and using advanced analytical and modeling tools to probe reactions across a wide range of temporal and spatial scales. Fundamental research efforts include the Joint Center for Energy Storage Research (JCESR),[126] an Energy Innovation Hub; Energy Frontier Research Centers; and single-investigator and small group research. JCESR, in particular, is developing advanced concepts in non-aqueous redox flow batteries using unique chemistries for anolyte and catholyte and has developed a unique membrane to block crossover during operation. Though far from commercialization currently, these concepts have potential to push the energy storage capacity to a higher level.

Zinc-Based Technologies

Ability to Provide Functional Requirements

In addition to the aforementioned hybrid flow battery based on a zinc anode, several other non-flow battery chemistries use low-cost zinc as a critical element of construction. Zinc-nickel technology is composed of a zinc-based anode, an alkaline electrolyte, and a nickel-hydroxide cathode. This technology is characterized by high power densities with energy densities in between lead-acid and lithium-ion technologies. The higher energy density and longer cycle life have made them attractive alternatives in UPS and automotive applications where lead-acid systems have been primarily used and may enable them to find application for shorter duration grid services. Another promising zinc-based chemistry currently being developed for grid-scale applications is based on the traditional Zn-MnO2 alkaline batteries. These cells use a zinc anode, an alkaline electrolyte, and a manganese-oxide cathode; this chemistry is the basis of most disposable batteries currently on the market. Modifications to the chemistry have enabled reversible charging of the cells. When combined with an estimated materials cost of <$20/kWh, a long shelf life, and an established manufacturing supply chain in the United States, these batteries are a potential candidate for low-cost grid storage.

Today's Technology Maturity Level

Zinc-nickel batteries, invented by Thomas Edison in 1901, are still being developed today as a low-cost, rechargeable storage solution to replace lead-acid batteries in applications requiring high power and longer lifetimes. Several commercial entities in the United States are pursuing development of the technology. Traditional Zn-MnO_2 or "alkaline" batteries, are one of the most produced battery chemistries in the world.

Constraints on Architecture

Manufacturing lines for rechargeable Zn-MnO_2 chemistries use the same materials and construction with modification to the chemistry to enable rechargeability.

[125] Basic Research Needs for Next Generation Electrical Energy Storage. https://science.osti.gov/-/media/bes/pdf/reports/2017/BRN_NGEES_rpt.pdf?la=en&hash=AE01DA34A0F1F17E42261F0B7BC416868C9C51AB

[126] Joint Center for Energy Storage Research. https://www.jcesr.org/

DOE Activity

Recent R&D efforts supported by ARPA-E and the Office of Electricity have focused on advancing reversible Zn-MnO_2 technology to the state of commercial viability. Early support by ARPA-E in New York enabled maturation of the technology and pilot-scale production of first-generation products. The DOE Office of Electricity's Energy Storage Program is supporting validation of the technology in selected field trials and R&D focused on improving materials utilization and developing of lower-cost materials to further the cost-performance position of the technology. Longer-term R&D is focused on using the full capability of Zn-MnO_2 systems and demonstrating cells with energy densities of 200 Wh/l and a cell cost lower than $50/kWh. These developments will enable the technology to compete with higher energy density technologies but at significantly lower costs and improved safety.

Utilizing Zn^{2+} and other multivalent cations in battery technologies (e.g., Mg^{2+}, Fe^{2+}) offer the potential of delivering more than one electron for every charge and discharge cycle, thereby increasing materials efficiency and potentially lower cost storage options. Research efforts on divalent materials are being conducted across the Office of Electricity, ARPA-E, and the Office of Science's Joint Center for Energy Storage Research.

Reversible Fuel Cells

Ability to Provide Functional Requirements

Reversible fuel cells (RFCs) are a subset of hydrogen energy storage (HES). HES is covered in detail under Chemical Energy Storage in this Appendix. RFCs are capable of operating in both power production (fuel cell) and energy storage (electrolysis) modes and are a promising way to store large amounts of energy at low cost. RFCs involve the production of hydrogen via electrolysis, in which electrical energy is used to split water molecules into hydrogen and oxygen gases, with the hydrogen (and sometimes oxygen) then being stored. This water-splitting process can be thought of as the RFC equivalent to charging a battery. In the fuel cell (discharge) mode, the stored hydrogen is then sent through the same electrochemical stack used for electrolysis to generate electricity and water, thereby, reversing the previous process. In this basic configuration, RFCs essentially act to store grid electricity as hydrogen for later conversion back to electricity. A discrete reversible fuel cell system uses separate electrolyzer and fuel cell stacks while the combination of these two processes into a single stack is commonly termed a unitized reversible fuel cell. Some advantages of carrying out fuel cell and electrolyzer operations in a single stack include significantly decreased cost (the fuel cell and electrolyzer electrochemical stacks are the costliest components), a smaller footprint, and system simplification.

Today's Technology Maturity Level

There have been very few RFC demonstrations with relevancy to energy storage applications. In the near term, it is anticipated that reversible fuel cell systems will consist of discrete fuel cell and electrolyzer stacks. These discrete reversible systems will require MW-scale, H_2-fueled stationary fuel cells capable of intermittent operation, which have historically received comparatively little attention. Unitized RFCs are at an early stage of R&D and must overcome challenges with the availability of materials that are stable and perform efficiently in both modes of operation, as well as cell, stack, and system architectures that provide flexibility and durability with switching operation modes. Achieving high stack and system roundtrip efficiencies is critical. Both high-temperature (>600°C) and low-temperature (<100°C) technologies are of interest, with high-temperature RFCs offering higher roundtrip efficiency and low-temperature RFCs offering better operational flexibility.

Constraints on Architecture

The round-trip efficiency of RFC systems is estimated to be <40% today for low temperature RFCs. With continued technical progress for increasing cell and stack performance, as well as improved understanding gained from building and demonstrating early, complete prototype systems, significantly higher round-trip efficiencies should be possible. High-temperature RFCs ultimately should be able to achieve system RTEs of ~70%; however, the high operating temperature could limit the technology to applications that do not require substantial idle time due to potential thermal management drawbacks. System RTEs for low-temperature RFCs are likely limited to ~50%; however, there is increased flexibility in energy storage duty cycles to which it would be applicable.

Both low-temperature and high-temperature RFC technologies require continued R&D in materials, structures, and interfaces to improve their performance, durability, and cost. A key challenge for low-temperature technologies is to develop effective bifunctional electrode materials and structures that can maintain electrode function and performance during repeated cycling between fuel cell and electrolysis modes without degradation, while maximizing both fuel cell and electrolyzer performance and efficiency without too much compromise relative to cells/stacks optimized solely for fuel cell or electrolyzer performance. A major source of the inefficiencies in PEM RFCs is the oxygen electrode due to differences in water management and catalyst requirements for fuel cell and electrolyzer operating modes. Obtaining a round-trip efficiency of PEM RFCs near that of discrete fuel cell and electrolyzer is a worthy, ambitious goal. Challenges for high-temperature RFCs include materials durability and effective thermal management with high-temperature heat, especially at the system level; material and structural degradation is a greater challenge than performance. The response time of high-temperature RFC stacks and systems is also an open question, where additional research could be conducted.

DOE Activity

The Hydrogen and Fuel Cell Technologies Office is supporting research and development for advancing both low and high-temperature unitized reversible fuel cells, including stacks. The FE Office is supporting the technology development of high temperature unitized reversible fuel cells greater than 600^{o}C. These efforts are focused on improving materials for efficient, durable operation in both fuel cell and electrolyzer modes of operation. Particularly for low-temperature technology, a material which works well in one mode of operation often functions poorly in the other mode of operation. To obtain a better understanding of how these unitized stacks will work in an overall system context, HFTO is also supporting projects that will demonstrate both low- and high-temperature RFC technologies in breadboard-type systems and FE supporting high temperature RFC (>600^{o}C). The findings will provide important insight into future designs and applications that will be based on technology advances being made at the cell level.

Electrochemical Capacitors

Ability to Provide Functional Requirements

Electrochemical capacitor technology, sometimes referred to as "supercapacitors" or "ultracapacitors," directly stores electrical charge on the surface of a material rather than converting the charge to another form, such as chemical energy in batteries. This makes supercapacitors highly reversible and efficient, with extremely fast response times (typically <1 second).[127] The technology is ideally suited for short-duration, high-power applications such as frequency regulation and voltage stabilization.

Today's Technology Maturity Level

The electric double-layer effort used in supercapacitors was first documented in 1957, but not actively developed until nearly a decade later.[128] Today, supercapacitors are a mature technology with common commercial deployments seen in multiple industrial sectors including automotive.

Constraints on Architecture

The devices may have longer useful lives since there is little breakdown in the electrochemical capacitor's ability to store energy electrostatically. Currently, electrochemical capacitors can store significantly more energy than dielectric and electrolytic capacitors; however, the technology is still cost prohibitive.[129]

DOE Activity

As evidenced by current market size, electrochemical capacitor technology is a relatively mature technology, with most R&D efforts conducted by industry for product improvements. Select R&D efforts within DOE are focused on extending the discharge duration or temperature stability of these technologies to enable more efficient operation of the power electronics used in energy storage systems.

Electromechanical

Pumped Storage Hydropower

Ability to Provide Functional Requirements

PSH currently accounts for about 95% of utility-scale storage deployments currently representing 21.6 GW[130] of capacity in the United States and >130 GW worldwide.[131] PSH provides large-scale energy storage, enabling balancing of variable renewable resources such as wind and solar PV on timescales from seconds to seasons, and it can also provide a suite of non-energy services to support reliable grid operation. While PSH was originally deployed principally to balance load variability so nuclear plants could operate as stable baseload generation, there is evidence the role of PSH is evolving to provide greater flexibility in response to increasing penetration of variable renewables. In recent years, for example, some PSH plants have switched their operations entirely to cycle twice per day rather than once to balance excess solar PV generation in the middle of the day.[132]

PSH employs off-peak electricity to pump water to an upper reservoir to store energy and releasing water through a hydroelectric turbine into the lower reservoir. Figure 14 shows a cutaway view of a

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127 J. Miller, "Perspective on electrochemical capacitor energy storage," *Applied Surface Science* 460 (2018) p 3–7.

128 Tecate Group, "Ultracapacitor Frequently Asked Questions." https://www.tecategroup.com/ultracapacitors-supercapacitors/ultracapacitor-FAQ.php

129 DOE Grid Energy Storage, December 2013. https://www.energy.gov/sites/prod/files/2014/09/f18/Grid%20Energy%20Storage%20December%202013.pdf

130 2017 Hydropower Market Report, p. 1. https://www.energy.gov/sites/prod/files/2018/04/f51/Hydropower%20Market%20Report.pdf

131 2017 Hydropower Market Report, p. 4. https://www.energy.gov/sites/prod/files/2018/04/f51/Hydropower%20Market%20Report.pdf

132 2017 Hydropower Market Report, p. 69. https://www.energy.gov/sites/prod/files/2018/04/f51/Hydropower%20Market%20Report.pdf

typical PSH plant.[133] PSH systems are classified as open-loop if they require continuous connection to a natural body of water, and closed-loop when upper and lower reservoirs are independent of continuous connection to natural bodies of water. These systems typically utilize >70% of their available capacity and can have response times from standstill to generation of 1–2 minutes. The time required to switch from generation to pumping mode are typically 4–7 minutes.[134,135]

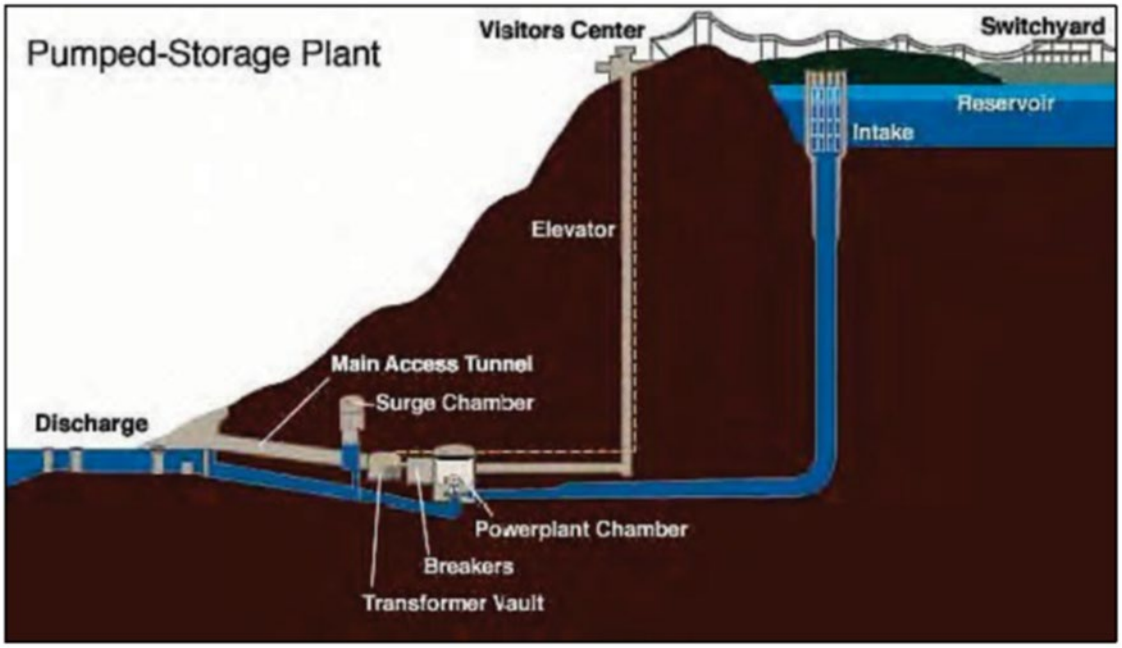


Figure 14. Cutaway diagram of a typical pumped hydro plant

Today's Technology Maturity Level

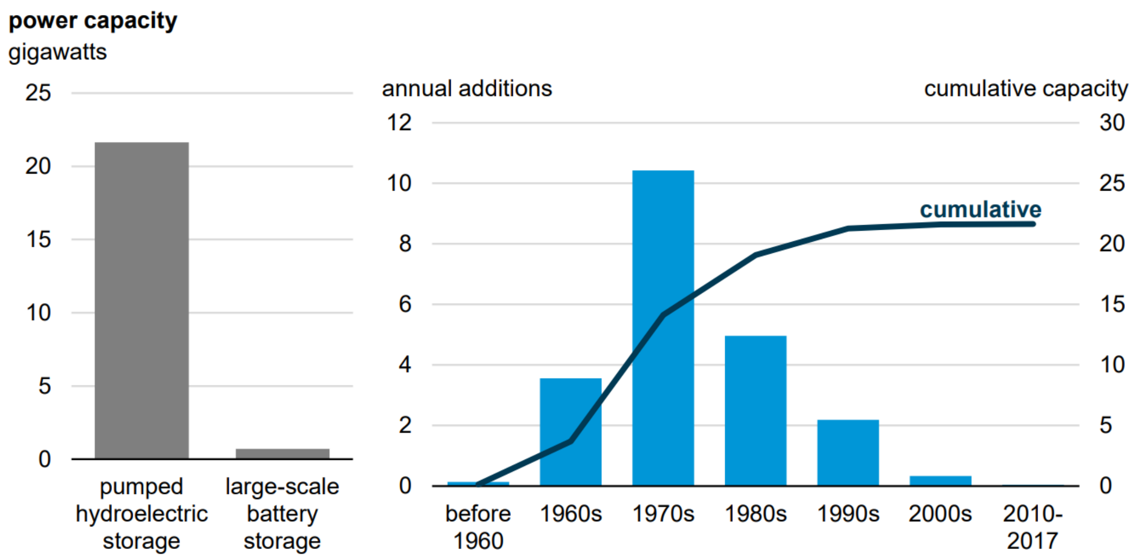
PSH technology has the highest capacity of all current storage technologies because its size is limited only by the size of the available upper and lower reservoirs. As seen in Figure 15, deployment of PSH peaked in the 1970s before significant concerns over land and water usage limited further deployments.[136] However, given PSH capabilities to generate GW-scale power with 10+ hour duration, it remains an attractive option for large-scale energy storage and provision of other grid services.

133 Sandia National Laboratories, "DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015, p. 15. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf

134 Modeling and Analysis of Value of Advanced Pumped Storage Hydropower in the U.S. Argonne National Laboratory, 2014. https://ceeesa.es.anl.gov/projects/psh/psh.html

135 R. O'Neil, Pumped Storage Hydropower Overview. Presented at First Solar, September 2018.

136 Preliminary Monthly Electric Generator Inventory (based on Form EIA-860M as a supplement to Form EIA-860).



Source: U.S. Energy Information Administration, Form EIA-860M, *Preliminary Monthly Electric Generator Inventory*

Figure 15. U.S. hydroelectric pumped storage capacity (1960–2017)[137]

Despite the relative technological maturity of PSH as an energy storage technology, a critical challenge is accurately understanding the value PSH provides to the system. PSH can offer a full range of services to the system, from GWs of capacity and GWhs of energy to fast-response reliability services and inertia. Co-optimizing provision of these services, some of which can be provided simultaneously and many of which involve tradeoffs with other services, is highly complex. Furthermore, the large size of some PSH plants can demand power system models that accommodate price-maker rather than price-taker approaches. Understanding the full stack of system values that PSH can provide, particularly as operations change, is an active area of research.

Constraints on Architecture

The most significant constraint on PSH deployments is obtaining suitable available land for the upper and lower reservoirs. Closed-loop systems that are not connected to a natural water source have less environmental impact and therefore greater flexibility in siting options. Closed-loop systems are the predominant technology being explored for future developments. Round-trip efficiencies, historically around 70%, have been improved over the years, with future R&D efforts by DOE targeting systems capable of >80% round-trip efficiencies.

For suitable sites, PSH deployments still face a number of barriers, including return on investment, capital costs, and time to commissioning. Return on investment can be highly uncertain because of the long asset lifetime for PSH; given the rapid rate of changes in electricity markets and generation mixes, Use Cases valuable today may change significantly over the 50+ year asset lifetime. High initial capital costs are a significant barrier for PSH, even while variable costs are low. Long time to commissioning adds to the uncertainty and difficulty of deploying new PSH plants; a ballpark estimate of total time from project initiation to operation is 10 years.

137 U.S. Energy Information Administration, "U.S. Battery Storage Market Trends," May 2018, p. 19.

DOE Activity

The WPTO supports development of innovative hydropower and PSH technologies to enable low-cost, reliable power for the Nation's electric grid. Given the challenges and opportunities associated with PSH operation, valuation, and deployment, WPTO's technology development and research activities are advancing fundamental understandings of the potential benefits of existing and prospective advanced PSH facilities. New technologies such as small modular PSH systems can reduce the geographical footprint and enable MW-scale PSH systems to be deployed, while advances in ternary PSH systems improve capacity utilization and increase response time and efficiency.

The hydropower subprogram continues research to quantify and understand the economic value of the services provided by hydropower and PSH, and the additional costs or technical requirements of operating hydropower systems in a changing grid. This research includes understanding the value of hydropower and PSH under future electric system conditions, quantifying the effect of flexibility constraints on plant capabilities and performance (e.g., from variations in water flows, plant designs, or license conditions), addressing critical technical barriers to effective operation of hydropower resources for reliability and economic dispatch, and identifying technology solutions that will preserve or enable hydropower capabilities to deliver services or system benefits competitively. In addition, the subprogram continues to drive innovation in the design of PSH, as traditional designs are capital intensive, limited in where they can be sited, and difficult to finance. New, transformative designs could reduce capital investment requirements, expand siting possibilities, and shorten development timeframes for new facilities, thus creating incentive for private investment. Ongoing analytical efforts include techno-economic analysis of the value of services that PSH can provide to the grid and work to understand new possible Use Cases for PSH in the evolving electricity system.

Compressed Air Energy Storage (CAES)

Ability to Provide Functional Requirements

CAES systems use off-peak electricity to compress air and store it in a reservoir, either underground in a suitable cavern or in an above-ground pressure vessel. When electricity is needed, the compressed air is heated, expanded, and directed through an expander or conventional turbine generator to produce electricity. A complete CAES system comprises compressors, expanders, air reservoirs, combustor, motor/generator, and control system.

Today's Technology Maturity Level

CAES was first proposed in 1949. The first system was placed into operation in 1978 in Huntorf, Germany,[138] making it one of the older technologies deployed for grid-scale energy storage.

Constraints on Architecture

The primary constraint for underground CAES is the limited appropriate geologic formations in a given utility's service area. As an underground technology, it has less environmental impact than PSH. Above-ground CAES technologies using pipes or pressure vessels do not have the geologic limitations but in general have been found to be more expensive on a $/kWh scale compared to other storage technologies.[139]

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138 J. Wang, et al. "Overview of Compressed Air Energy Storage and Technology Development," *Energies 2017*, 10, 991.

139 Sandia National Laboratories. "DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA," SAND2015-1002, February 2015, p. 40. https://www.sandia.gov/ess-ssl/publications/SAND2015-1002.pdf

DOE Activity

The Office of Electricity supported demonstration efforts of modular CAES technology under American Recovery and Reinvestment Act grants beginning in 2010, which were unable to demonstrate financial viability.[140] Early-stage R&D on potential novel designs that can overcome technical and economic barriers is limited.

FE has complete studies evaluating the benefits of integrating CAES with fossil power plants to enhance flexibility. Additionally, FE may support the integration of energy storage technologies, potentially including CAES, with fossil power plants through a FY20 FOA.

Liquid Air Energy Storage (LAES)

Ability to Provide Functional Requirements

LAES, also known as cryogenic energy storage, uses excess power to compress and liquefy dried/CO_2-free air. When power is needed, the air is heated to its boiling point and expanded through a generator. Efficiency is increased by capturing and storing heat from compression and cold from expansion, which aids the ability to cycle on a daily basis. LAES offers noteworthy heat integration opportunities as well in hybrid applications with power generating facilities and large industrial assets. A significant benefit of the technology includes an unlimited supply of the storage medium, not limited by geography, hence limiting costs for long-duration storage.

Today's Technology Maturity Level

The compression equipment and power generators come from established supply chains in mature industries. The technological innovation here is using them for grid storage and in hybrid applications. Pilot Plant (2.5MWh) in Slough, UK, was commissioned in 2014, followed by a 15MWh unit in Bury, Greater Manchester, UK. Another 50MW/250MWh project is located in the north of England at a decommissioned thermal plant site. Highview recently secured the first cryogenic storage deal in the United States, in partnership with Encore Renewable Energy. The project will serve the Vermont grid with at least 50 megawatts/400 megawatt-hours. The developers are targeting an online date at the end of 2022 and will provide an array of services including renewables integration, grid inertia, frequency regulation, transmission constraint relief, and more.

Constraints on Architecture

Efficiency and cost improvements may be somewhat limited given mature nature of machinery. Opportunities to integrate in a system context could enhance overall value.

DOE Activity

DOE activity in this space is relatively limited. DOE's Office of Fossil Energy has several projects doing optimization studies of integrating various energy storage technologies with coal and gas power plants, including liquid air energy storage. These projects are using standard Aspen modeling of individual cases as well as dynamic, high-fidelity modeling and optimization of the flow sheets. FE has a long history of investigating air separation technologies that can be used for oxy-combustion and gasification of fossil fuels to enable CO_2 capture processes for power and chemicals production.

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140 "Energy Storage Activities in the United States Electricity Grid," May 2011. https://www.energy.gov/sites/prod/files/oeprod/DocumentsandMedia/FINAL_DOE_Report-Storage_Activities_5-1-11.pdf

Flywheels

Ability to Provide Functional Requirements

Flywheels store energy in the form of the angular momentum of a spinning mass called a rotor and are charged and discharged electrically using a dual-purpose motor/generator connected to the rotor. Most flywheel systems use a containment vessel around the rotor for improved safety and performance. Flywheels are characterized by fast response times (around 4 ms), long cycle life, and high power density,[141] making them ideal candidates for power quality applications like frequency regulation. The kinetic energy (and storage capacity) of the flywheel is directly proportional to the mass of the rotor, making these systems very heavy. Modern flywheels may require 1 metric ton of mass to generate 25 kWh.[142]

Today's Technology Maturity Level

Flywheel technologies have long been used in industry to dampen variations in electric loads. Many shapes of flywheels have been used, ranging from the wagon-wheel configuration found in stationary steam engines to the mass-produced, multipurpose disks found in modern automotive engines.

Constraints on Architecture

Flywheels self-discharge at a much higher rate than other storage mediums and can be hazardous if not designed for safety. One of the most significant constraints on the storage architecture is the lack of installed manufacturing base to support lower cost systems.

DOE Activity

The Office of Electricity has active R&D supporting development of new materials that can enable the mass requirements for flywheels at a much lower cost while achieving similar performance and reliability standards to today's technology. ARPA-E has also supported several novel flywheel technologies aimed at lower costs and longer durations.

Chemical and Thermal Storage

Chemical and thermal energy storage focuses on the media and containment technologies (not already included in the bidirectional electrical storage or flexible generation and load categories) that are capable of harnessing chemical or thermal energy for conversion to or from electricity. Thermal energy storage technologies include high-temperature reservoirs such as molten salt, phase change materials, concrete and geothermal resources as well as lower-temperature storage, including additional geothermal applications, phase change materials and the thermal mass of buildings. These thermal reservoirs can be discharged to provide heat for a variety of applications, including electricity generation through a heat engine, industrial processes, or building uses. Because certain thermal energy storage applications can meet the relatively modest temperature requirements of space heating and cooling applications, they can also potentially offset demands on the grid that would otherwise manifest as electrical heating or cooling loads. Chemical energy storage includes hydrogen and other energy-dense

[141] M.E. Amiryar and K.R. Pullen, "A Review of Flywheel Energy Storage System Technologies and Their Applications," *Appl. Sci. 2017*, 7, 286; doi:10.3390/app7030286.

[142] D. Bender, "Flywheels," Sandia National Laboratories, May 2015. https://www.sandia.gov/ess-ssl/publications/SAND2015-3976.pdf

chemicals produced from diverse domestic energy sources (e.g., renewables, nuclear, and fossil). These chemicals can be used for power-to-gas, synthetic fuels, ammonia, or other one-way forms of storage.

Chemical Energy Storage

Chemical energy storage includes hydrogen and other energy-carrying chemicals that can be produced using diverse domestic energy sources (e.g., renewables, nuclear, and fossil), enabling ultra-high energy density, long duration/seasonal storage, and the ability to couple and decouple from the grid in unique ways.[143] Hydrogen and other hydrogen-rich chemical energy carriers can be synthesized at industrial scales utilizing the nation's energy resources for subsequent use in various one-way energy storage applications (such as power-to-gas, power-to-liquids, small and large-scale power generation, steel manufacturing, and heavy-duty vehicles, among others), as well as bidirectional storage (e.g., using reversible fuel cells, described in the "Bidirectional Energy Storage" section).

Hydrogen is itself a unique and versatile energy carrier but is also a critical component of other energy-rich chemical carriers (such as methanol, ammonia, etc.) that can be used for large-scale energy storage and transport, as well as other industrial end uses. This versatility is foundational to H2@Scale, a DOE initiative[144] that supports innovations to produce, store, transport, and utilize hydrogen and hydrogen-rich chemicals across multiple sectors. As illustrated in Figure 16, H2@Scale enables—rather than competes with—energy pathways across applications and sectors. Primary energy sources—fossil fuels, nuclear, and renewables—are shown on the left. These sources are used to provide energy for the conventional electric grid, shown in red, to produce hydrogen, or some of these resources (e.g., fossil fuels or biomass) can generate hydrogen directly, bypassing the electric grid. Once hydrogen is produced, it can be stored and fed back to the electric grid through power conversion devices (such as turbines or fuel cells), or injected into the natural gas 'grid,' as shown with the tan circle. These approaches are examples of bidirectional and one-way chemical energy storage, respectively. The hydrogen can also be used for additional revenue streams in applications such as vehicle refueling, steel manufacturing, and ammonia synthesis, or combined with CO_2 for synthetic fuel production, as shown on the right side of the figure. As an example of large-scale energy storage and transport, hydrogen and the other hydrogen-rich chemical carriers such as methanol, ammonia and liquid organic chemicals can also be used for export through ship tankers similar to what is currently underway with liquefied natural gas. A distinguishing feature of hydrogen energy storage systems is this flexibility to use the stored hydrogen in multiple ways.

143 Natural gas storage is an incumbent embodiment of chemical energy storage that plays a vital role in maintaining the reliability of supply needed to meet the demands of the U.S. Natural gas in storage also serves as insurance against any unforeseen accidents, natural disasters, or other occurrences that may affect the production or delivery of energy. http://naturalgas.org/naturalgas/storage/

144 https://www.energy.gov/eere/fuelcells/h2-scale

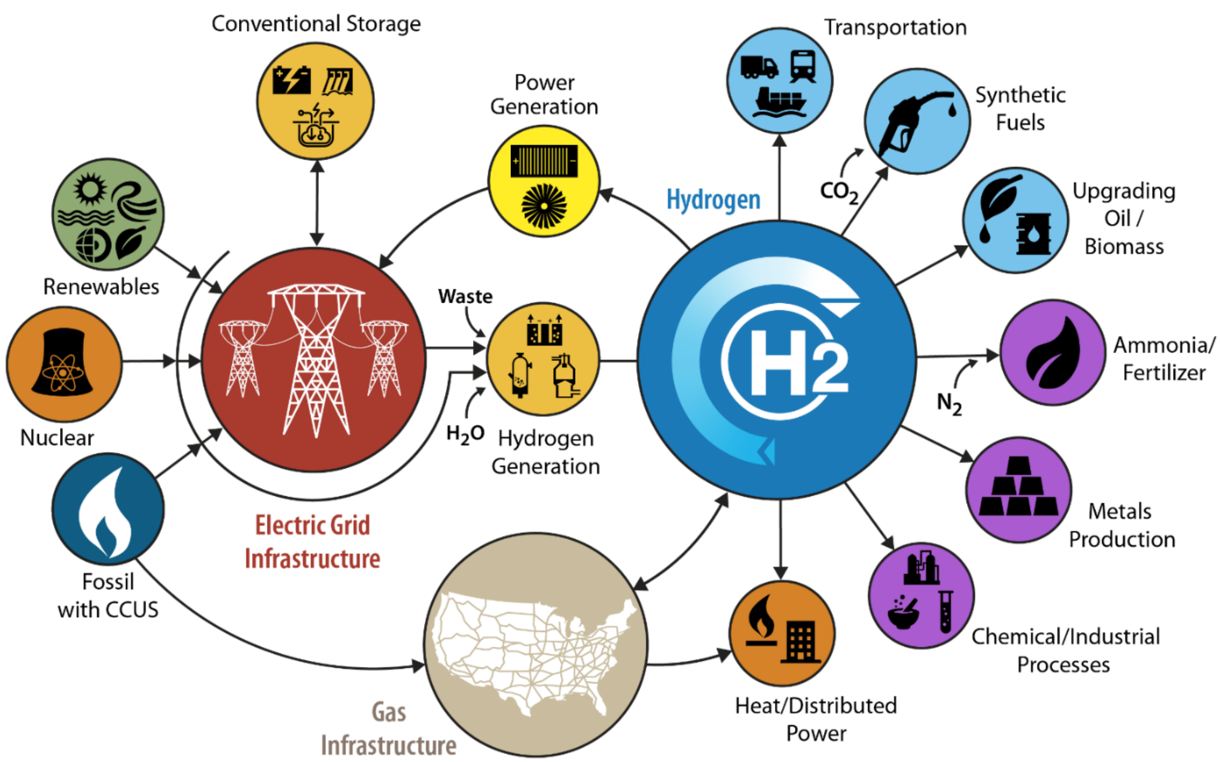

Figure 16. The H2@Scale vision: hydrogen can play a central role in both bidirectional and one-way energy storage[145]

Hydrogen

Ability to Provide Functional Requirements

Hydrogen energy storage (HES) offers unique benefits beyond the potential for long-term, seasonal energy storage. Examples include grid leveling and stabilization services and coupling with intermittent renewable energy sources to enable reliable, emission-free electricity. In these systems, H_2 is produced via electrolysis in which electrical energy is used to split water molecules into hydrogen and oxygen gas with the hydrogen then being stored. This water-splitting process is the HES equivalent of charging a battery. Electrolyzers have a fast-acting dynamic response which can further support the grid via ancillary services and demand response. In power generation (discharge) mode, the stored hydrogen is then sent to a fuel cell or other power conversion device to generate electricity and water, thereby reversing the process. In addition to this bidirectional energy storage application, there are options for one-way energy storage with some examples mentioned above. Compared to other energy storage technologies, another advantage of HES systems is the flexibility to deploy the hydrogen generated to other markets and customers, potentially at higher value than grid electricity. Additionally, its energy storage capacity can be scaled independently from the power and hydrogen production rates. Hydrogen can be stored in immense underground salt caverns, which opens up opportunities for seasonal energy storage. Today, thousands of tons of hydrogen are stored in salt caverns to support differences in seasonal demand experienced by the petrochemical industry.

145 https://www.energy.gov/eere/fuelcells/h2scale

Although there are several processes for producing hydrogen at scales for energy storage, water splitting via electrolysis (a process illustrated in Figure 17) is key to the implementation of HES in the near term.

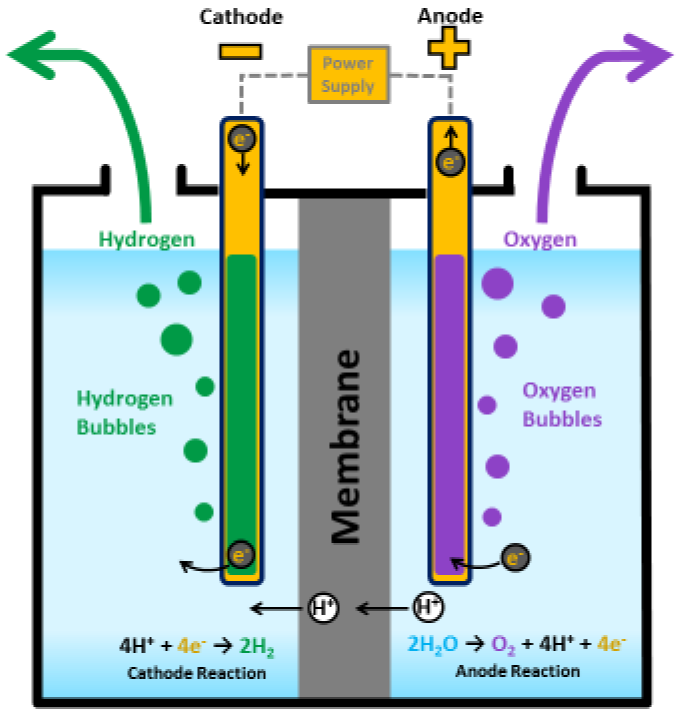

Figure 17. General operation of electrolysis process for water splitting

Process shown schematically for a proton-conducting system in which hydrogen is produced at the negatively-biased cathode, oxygen produced at the positively-biased anode, and H+ ions transported through a separating membrane.

Electrolyzer technologies can be broadly classified as low-temperature or high-temperature based on their operating temperature ranges. Low-temperature electrolysis, generally operated below 100°C, includes liquid alkaline, proton exchange membrane (PEM), and alkaline exchange membrane (AEM) technologies. Liquid alkaline electrolysis systems have been established for over 100 years and have a large manufacturing base, but lack response, efficiency, and system footprint when compared with the membrane-based options. PEM and AEM technologies are distinguished by the conductive species through the electrolyte or membrane (H^+ and OH^- for PEM and AEM, respectively). The former has recently reached MW-size commercial systems and has a fast, dynamic response, opening up opportunities to serve grid ancillary services roles such as frequency regulation. High-temperature electrolysis (HTE) typically operates above 550°C. The leading high-temperature electrolysis technology under development utilizes solid oxide electrolyzer cells (SOECs) which are based on similar materials to those used in solid oxide fuel cells. SOECs offer the advantage of high-efficiency hydrogen production, particularly when used in conjunction with high-temperature process heat, by harnessing both heat and electricity to generate the hydrogen. Integration of HTE with nuclear power plants provides an opportunity to utilize process heat while keeping existing power plants operational when they may otherwise be curtailed.

A longer-term solution for large-scale renewable hydrogen production is direct solar water splitting that bypasses the need for electricity input. The two main solar approaches are the photoelectrochemical (PEC) and solar thermochemical hydrogen (STCH) pathways. PEC technology converts solar energy using semiconductor photoelectrodes and photocatalysts, offers the potential for high solar-to-hydrogen (STH) efficiency (>30% under ideal circumstances[146]), and is low-cost, but it is still in an early stage of development. STCH is a chemical-looping technology using high temperatures from concentrated solar power to drive thermochemical cycles based on reduction/oxidation (redox) materials. It also offers potential to achieve high theoretical conversion efficiencies, but it is still early stage. Other early stage approaches to hydrogen production include biological-based conversion of biomass or waste streams, for example using fermentation[147] or microbial electrolysis.

Storing the chemical energy of hydrogen produced through electricity or directly from solar or other energy sources can be achieved through a number of different approaches. Although hydrogen has the highest energy content by weight of conventional fuels (nearly three times more than natural gas, gasoline and diesel), in gaseous form the volumetric energy density is low. As a result, it is most often physically stored as either a compressed gas in pressure vessels (at pressures up to 10,000 psi, depending on the storage application) or in liquid form (20K) in insulated cryogenic vessels. Material-based hydrogen storage options such as adsorbents, metal hydrides, and hydrogen carriers are also being pursued, offering the potential for comparable hydrogen storage densities, but at near-ambient operating conditions without the need for high pressure or liquefaction. For long-duration energy storage, hydrogen can also be stored in bulk in caverns (e.g., underground rock-lined or salt caverns), available in certain specific geographical areas.

For bidirectional HES applications, power conversion of the stored chemical energy to electricity can be achieved using turbine or fuel cell technologies, both offering highly efficient energy conversion with low emissions. Another approach is to combine the electrolysis and fuel cell functions into a single electrochemical stack, which is conventionally referred to as a reversible fuel cell (RFC). This integrated approach offers cost savings through system simplification and reduced footprint (compared with combining separate electrolyzer and fuel cell systems), but it is at an earlier development stage. RFCs are covered in detail in the Bidirectional Storage section of this Appendix.

Today's Technology Maturity Level

The different technologies and infrastructure for hydrogen production, storage, and utilization exist today at various levels of maturity and cost-competitiveness. While many are commercially available, ongoing research and development efforts continue to improve performance levels and decrease costs to levels necessary for widespread adoption in energy storage applications. Hydrogen today is a major chemical feedstock in other industrial applications such as ammonia production and oil refining, where the U.S. uses approximately 10 million metric tons annually (approximately one-seventh of global production), supplied mainly from reforming low-cost natural gas through commercially mature processes such as steam methane reforming (SMR), at a hydrogen cost <\$1.5/kg. Advances in modular, tightly integrated systems with reductions in fuel processing could lower the costs to below \$1 per

[146] H. Döscher, J.F. Geisz, T.G. Deutsch, J.A. Turner, "Sunlight Absorption in Water– Efficiency and Design Implications for Photoelectrochemical Devices," *Energy & Environmental Science* 7 (9), (2014): 2951-2956.

[147] Randolph, K., Studer, S. "Hydrogen Production Cost from Fermentation." https://www.hydrogen.energy.gov/pdfs/16016_h2_production_cost_fermentation.pdf

kilogram. Coal capture utilization and storage (CCUS) can be used with SMR or with gasification of coal, biomass, and waste plastics, with potential to produce hydrogen at less than $2/kg. While the hydrogen technologies relevant to energy storage of diverse renewable and nuclear-based resources are less mature than SMR, development efforts target comparable levels of scale and hydrogen costs. The resulting diversification of the hydrogen supply will be a key enabler for chemical energy storage applications, and can also benefit industries across sectors, providing resilience to potential price volatility and offering new regional opportunities leveraging local resources.

Affordable, industrial-scale electrolysis is critical to cost-effective HES. Liquid-alkaline electrolysis has been commercially mature for decades, with historic implementation at the multi-MW scale in industrial applications such as ammonia production. The membrane-based electrolyzer technologies offer advantages in current density, reduced footprint and rapid response time that are well-suited to renewable integration and HES implementation, but these are less mature. Today, membrane-based PEM electrolyzers provide only a small portion of hydrogen in the United States, primarily for specialized applications that require relatively small volumes of high-purity hydrogen.[148] Manufacturing of low-temperature PEM electrolyzers in the United States today is approximately 10 MW per year,[149] however manufacturing demand is expanding with growing interest in grid integration opportunities enabled by PEM performance. Although technology status varies depending on existing and emerging deployments, current PEM technology can convert electricity to hydrogen at an efficiency of approximately 60% (LHV) and estimates for durability are about 40,000 hours. Compared with the low-temperature technologies, high-temperature electrolyzers are a step behind in maturity level. Prototypes have been demonstrated at the stack and system levels with high conversion efficiencies (electrical utilization >95%)[150] but with remaining challenges in durability. Technology advances are ongoing in both low- and high-temperature electrolyzers. These, coupled with cost reductions from increased electrolyzer manufacturing volumes and low renewable electricity costs, are making hydrogen an attractive option for energy storage applications.

The direct solar water-splitting technologies, PEC and STCH, are longer-term options at the material discovery and development stage, with current demonstrations at the lab- and small-prototype scales. Though these approaches theoretically offer the potential for solar-to-hydrogen (STH) conversion efficiencies in excess of 25% (LHV), prototype demonstrations to date have been limited to about 10% and 5% STH for PEC and STCH, respectively. Effectively understanding and investigating trade-offs between efficiency, durability, and cost parameters of the materials, devices, and systems remain key to realizing the full potential of these pathways. Biological approaches for converting biomass or waste streams to hydrogen leveraging thermal, electric, or solar energy are also at an early stage, with ongoing bio- and genetic-engineering research underway to optimize hydrogen yield from microorganisms. Nearer-term approaches such as biomass/waste gasification are also pathways currently being pursued by industry and can complement electrolysis-based systems by utilizing biomass or waste resources as baseload options in contrast to intermittent renewables.

148 Suresh, B., et al. (2018). "Hydrogen." IHS Markit, *Chemical Economics Handbook*.

149 Peterson, D., Vickers, J., Desantis, D. "Hydrogen Production Cost From PEM Electrolysis—2019." https://www.hydrogen.energy.gov/pdfs/19009_h2_production_cost_pem_electrolysis_2019.pdf

150 Peterson, D., Miller, E. "Hydrogen Production Cost from Solid Oxide Electrolysis." https://www.hydrogen.energy.gov/pdfs/16014_h2_production_cost_solid_oxide_electrolysis.pdf

In terms of hydrogen storage, compressed gaseous hydrogen is currently being stored in commercially available pressure vessels, such as metal tanks. The carbon-fiber-reinforced tanks typically used for the very high-pressure applications (e.g., 10,000 psi) are available, but expensive. Ongoing R&D is focused on cost reductions in these tanks. Large-scale gaseous hydrogen systems supporting long-duration or seasonal energy storage are available, but geologically limited to specific regions. There are several geologic storage sites worldwide in which hydrogen is currently being stored for use primarily by the oil, natural gas, and compressed air industries. The United States is home to three such salt caverns, including the world's largest located in Beaumont, Texas.[151,152] Other types of geological formations are being explored to store large quantities of hydrogen, or as a potential alternative to the current natural gas infrastructure. These include saline aquifers, depleted natural gas or oil reservoirs, and engineered hard rock reservoirs.[153] Within DOE, FE is pursuing rigorously the option of geologic storage within salt caverns, saline aquifers, depleted natural gas or oil reservoirs, and engineered hard rock reservoirs that can be used as long-term storage mechanisms. Further analysis could increase the geographic availability of geologic storage sites, including expansion beyond salt and hard rock caverns to other options such as depleted oil and gas reservoirs, depleted aquifers, and deep-sea storage. Liquid hydrogen is another option for large-scale chemical storage and transport applications, utilizing commercial cryogenic liquefaction and storage equipment. Cost reductions in such equipment are the focus of ongoing R&D.

Constraints on Architecture

Chemical energy storage systems based on hydrogen and fuel cell technologies are still in the process of being demonstrated in complete, multi-MW-scale integrated systems operating under real-world, grid-relevant operating conditions. This phase is critical to demonstrate viability and to appropriately de-risk the technologies to utilities and other decision-makers that would be purchasing and implementing these systems. Demonstration of reliable, fast-acting dynamic response of electrolyzers at-scale to support the grid through ancillary services and demand response is also ongoing. Large-scale systems for energy storage, stabilization, resiliency, and dispatch management of electric grid systems with high renewable energy penetration are all being validated; while major components are advanced enough to enable these efforts, continued cost reductions through technology improvements and economies of scale will be needed.

A specific concern in hydrogen-based bidirectional storage is the low round-trip efficiency (RTE) based on today's electrolyzer and fuel cell technologies, estimated to be <40% today. Technical progress and improved understanding gained from ongoing research, development, and demonstration activities aims to achieve RTEs of >70% with advanced technologies such as high-temperature reversible fuel cells. Independent of the technology advances, the ability to combine bidirectional energy storage applications with one-way storage opportunities for additional revenue streams could relax the round-trip efficiency requirements. Additional analysis work through H2@Scale is being conducted to home in

151 Kruck, O. et al. "Assessment of the potential, the actors and relevant business cases for large scale and seasonal storage of renewable electricity by hydrogen underground storage in Europe." HyUnder Deliverable 3.1. Overview on all Known Underground Storage Technologies for Hydrogen. August 14, 2013. http://hyunder.eu/wp-content/uploads/2016/01/D3.1_Overview-of-all-known-underground-storage-technologies.pdf

152 Air Liquide. "USA: Air Liquide operates the world's largest hydrogen storage facility". Press Release. January 3, 2017: https://www.airliquide.com/media/usa-air-liquide-operates-world-largest-hydrogen-storage-facility

153 A. S. Lord, P. H. Kobos and D. J. Borns, "Geologic storage of hydrogen: Scaling up to meet city transportation demands," International Journal of Hydrogen Energy, vol. 39, no. 28, pp. 15570-15582, 2014.

on the best opportunities for hydrogen energy storage options to be competitive with other energy storage technologies.

Even with advanced electrolysis technologies, the price of electricity can account for over 80% of the cost of hydrogen production from water splitting, emphasizing the important role of low electricity prices in viable H2@Scale scenarios.[154] Sufficiently low electricity prices, however, are projected to occur more frequently in coming decades, given high regional penetrations of renewables on the grid. Intermittency of these renewable energy sources emphasizes the need for good dynamic response. Additional verification and validation of electrolyzer performance (including efficiency and durability) under dynamic grid conditions is ongoing. Beyond dynamic operations with low-cost electricity, further capital cost reductions, improved electrical efficiency, and improved durability will make electrolysis a cost competitive solution.

DOE Activity

DOE's Hydrogen Program, led by EERE's Hydrogen and Fuel Cell Technologies Office (HFTO), has a central role in advancing key technologies relevant to H2@Scale and energy storage opportunities.[155] The focus is on developing and scaling up affordable hydrogen and fuel cell technology options for expanded supply and demand, enabled by early stage applied R&D and by leveraging the private sector for large scale demonstrations. To focus its priorities for research, development, and demonstration, the Program has defined goals with specific targets through techno-economic analysis and extensive input from industry and other relevant stakeholders. The Program's broad portfolio of analytical and research activities areas includes:

- **Overarching systems analysis** to define market opportunities, assess technology pathways as well as impact potential and gaps, and to help guide the overall R&D
- **Hydrogen technologies** to enable hydrogen production, infrastructure, and storage technologies that meet cost, efficiency, reliability, and other application-dependent metrics
- **Fuel cell technologies** to enable affordable and durable fuel cells for applications across sectors, with a focus on heavy-duty applications
- **Technology acceleration**, including systems integration such as grid integration activities, to demonstrate the benefits of electrolyzers in a systems context and in the greater energy landscape. Enabling manufacturing and first-of-a-kind demonstrations, as well as safety, codes and standards, and workforce development are all a key part of technology acceleration.

The Program has a two-pronged strategy to achieve its mission: (1) accelerate R&D to enable cost reductions and demonstrate advances, including integrated systems in the near term, along with (2) early stage research to enable innovation and leapfrog current approaches to meet ultimate targets in the long term. Specific R&D strategies of relevance to HES include developing advanced components and systems for multi-MW-scale electrolyzers at high volume as well as demonstrating grid integrated hydrogen systems in line with H2@Scale. Activities in the different research areas are supported through various funding mechanisms, including FOAs, Lab Calls, CRADAs, and others. Specific topics in

[154] Peterson, D., Vickers, J., and DeSantis, D. "Hydrogen Production Cost from PEM Electrolysis—2019." https://www.hydrogen.energy.gov/pdfs/19009_h2_production_cost_pem_electrolysis_2019.pdf

[155] "U.S. Department of Energy Hydrogen Program Plan -- 2020." https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

these areas are developed by the Program guided by extensive stakeholder engagement, including RFIs and workshops.

Through H2@Scale projects with industry, academia, and the National Labs, large-scale integrated systems for hydrogen-based chemical energy storage are being designed, evaluated, and demonstrated in first-of-a-kind prototypes. These include grid energy storage projects, incorporating electrolyzer and hydrogen storage systems, to validate renewable hydrogen-based grid management systems. Other examples include hybrid nuclear hydrogen production systems (in collaboration with DOE's Office of Nuclear Energy) demonstrating the value-add to the nuclear baseload of production hydrogen through low and high-temperature electrolyzers. World-class resources at the National Labs, including real-world and virtual electrolyzer test facilities at NREL (ESIF, and in the future at ARIES) and INL are important contributors to such efforts.

The Program's early stage applied R&D for improving performance and reducing costs in hydrogen production, storage, and utilization technologies leverages an innovative 'consortia' approach that it has developed in conjunction with the DOE Energy Materials Network.[156] The DOE-funded and -managed consortia in this approach are composed of core National Laboratories offering state-of-the-art capabilities and expertise that university and industry partners can access to accelerate materials- and system-level breakthroughs and innovations. The multidisciplinary team approach effectively leverages state-of-the-art resources in theory, synthesis and characterization at the DOE National Laboratories, including innovative combinatorial and high-throughput techniques as well as advanced data management and informatics. The consortia are based on common foundational principles to create the collaborative research environment for rapidly building on R&D successes. Program-sponsored consortia relevant to energy storage and H2@Scale include:

- HydroGEN Consortium on Advanced Water Splitting Materials
- HyMARC Consortium on Materials-Based Hydrogen Storage
- H-Mat Consortium on Hydrogen Compatible Materials
- ElectroCat Consortium on Platinum Group Metal-Free Electrocatalysts for Fuel Cells.

Additional consortia leveraging foundational research progress to advance scalable hydrogen and fuel cell technologies include:

- M2FCT Consortium on Durable, High-Performance Heavy-Duty Fuel Cells
- H2NEW Consortium on Durable and Efficient Large-Scale Electrolyzers.

In parallel with the research activities within the EERE Hydrogen and Fuel Cell Technologies Office, collaborative work on hydrogen and fuel cell technologies relevant to chemical energy storage is ongoing with other DOE offices.

The Office of Fossil Energy (FE) is focused on technological advancements to enable an expanding domestic hydrogen economy, including four major R&D focus areas:

1. Carbon-free hydrogen production using gasification and reforming technologies
2. Large-scale hydrogen infrastructure

[156] U.S. Department of Energy, Energy Materials Network. https://www.energy.gov/eere/energy-materials-network/energy-materials-network

3. Hydrogen and chemical storage
4. End use in electricity and other energy sectors.

These focus areas were identified in FE's Hydrogen Strategy. FE's Advanced Energy Storage Program is investing in technologies that integrate energy storage, including hydrogen, with fossil-based assets (including both small-scale and large power generators). It is supporting analysis projects that are reviewing the energy storage technology landscape and doing plant-level analyses to identify promising combinations of specific energy storage technologies with various asset classes. H_2 and ammonia energy storage, both familiar to FE through prior work, including commercial-scale demonstrations on Integrated Gasification Combined Cycle units, are included. Through the Coal FIRST initiative, FE is investing in four pre-FEED studies, two of which include energy storage integrated with gasification facilities that are producing hydrogen from the gasification of coal, biomass, and waste plastics with CCUS. Several of these include a chemical energy storage medium. The energy storage component of these designs tends to be in the 50 MW scale, with technologies such as large battery, chemical, thermal, and hydrogen storage to provide a range of services to the plant and grid. FE's Gasification Program is investing in concepts that utilize waste plastics and biomass to create hydrogen through gasification. FE's Advanced Turbine Program has invested in H_2 Turbines for over a decade including addressing combustion, materials, and other key challenges to realize turbines capable of high-H_2 concentrations now being deployed commercially.

Additionally, the Office of Basic Energy Sciences is supporting a broad portfolio of fundamental research on hydrogen storage, membranes, nanoscale catalysts, solar hydrogen production and bio-inspired hydrogen production. The scientific discoveries are conveyed to the Hydrogen and Fuel Cell Technologies Office through close coordination within DOE.

Chemical Carriers

Ability to Provide Functional Requirements

Hydrogen carriers, where hydrogen is bound to liquid or solid materials for facile movement and subsequent release, are an emerging option for energy transport and storage. These include materials such as hydrocarbon liquids, simple gases like ammonia, or chemical hydrogen storage materials. Carriers have been deployed in prototype demonstrations to supply hydrogen to industrial applications and are currently being explored for use in bulk exporting of hydrogen onboard marine vessels. They have also received attention for their potential advantages to support backup power systems for data centers. The key advantage to hydrogen carriers is their ability to transport hydrogen at greater densities than liquid hydrogen at near ambient temperatures and pressures, without complications with hydrogen boil-off or the need for cost- and energy-intensive liquefaction processes. Furthermore, existing infrastructure, such as pipelines and tanker trucks used in the oil and gas industry, may be able to be used to transport and store some hydrogen carriers. Existing commercial production facilities for the carriers can also be leveraged.

Hydrogen carriers fall broadly into two categories: (1) one-way carriers—materials for which the discharge of hydrogen results in the formation of a benign byproduct that is released into the environment (e.g., ammonia, NH_3, which decomposes into hydrogen and nitrogen gases); and (2) two-way carriers—materials that can be cycled between the hydrogenated and dehydrogenated phases (e.g., methylcyclohexane, which is dehydrogenated to form hydrogen and toluene, where the toluene can then be rehydrogenated back to methylcyclohexane). Both of these options are being investigated and have the potential to provide improvements over current hydrogen delivery and storage methods.

Today's Technology Maturity Level

There are two significant industrial prototype demonstrations currently underway utilizing hydrogen carriers. The Japanese company Chiyoda has developed a novel catalyst system to improve the dehydrogenation of methylcyclohexane (MCH) to toluene, which enables a more efficient transport of hydrogen using the two-way carrier compared with conventional transport of hydrogen gas or liquid. The storage and transport of MCH/toluene is being demonstrated on a shipping route between Brunei and Japan, where the dehydrogenation process will take place to provide hydrogen for power generation. The German company Hydrogenious has developed a process using a similar carrier molecule, dibenzyltoluene, and is demonstrating prototype systems for various applications.

While these initial examples demonstrate the potential benefits of carriers, the general technology is still at a relatively low maturity. The most significant hurdle to increased advancement of carriers is the development of effective ways to facilitate dehydrogenation and subsequent purification of hydrogen for specific end uses. It is unlikely that one specific carrier material will solve the needs of all applications, but rather that several different carrier materials will be developed, tailored the needs of specific uses.

Constraints on Architecture

The need for hydrogenation or dehydrogenation systems has a significant impact on the overall cost and energy benefits of carrier materials and is a constraint on the more widespread use of carriers. One-way carriers have slightly less concerns in this regard, as the byproduct of dehydrogenation is simply released to the environment without subsequent rehydrogenation. Dehydrogenation systems require advanced catalyst technologies and the use of elevated temperature operation. Another concern is the location of carrier dehydrogenation facilities. Depending on the specific end use, co-location of dehydrogenation and hydrogen use may not be possible, and still requires some limited traditional transport of gaseous hydrogen from a facility to the end use location. This impacts the overall efficiency of the hydrogen delivery process using the carrier.

DOE Activity

HFTO's Hydrogen Storage program has funded activities on hydrogen storage materials, including chemical carriers, for many years. Current activities on carriers are being pursued by HyMARC, an EMN consortium.[157] Their work on carriers is focused on increasing hydrogen capacity and improving charge/discharge rates, reversibility, and overall round-trip efficiency. The group is focused on a wide variety of potential carrier materials, with projects underway investigating the potential of traditional liquid carrier molecules (e.g., formic acid, hydrocarbons), advanced chemical hydrides, and even solid adsorbents. The group is also engaged in analysis work to elucidate the benefits of carriers for various applications, and to evaluate needs and targets for carrier materials to enable their utilization.

[157] https://www.hymarc.org/

Thermal Storage

Thermal Storage with Generation

Thermal storage integrated with Generation is covered in the "Flexible Generation and Controllable Loads" section of this Appendix.

Thermal Storage within Buildings

Thermal storage within buildings is covered in the "Flexible Generation and Controllable Loads" section of this Appendix.

Reservoir Thermal Energy Storage and other Geothermal Advanced Energy Storage Technologies

Ability to Provide Functional Requirement

Reservoir Thermal Energy Storage (RTES) uses fluids to transmit and store heat, while using the insulation capacity of geologic materials to limit thermal energy loss during the storage period. RTES targets subsurface zones of permeability that are poorly connected with regional aquifers. RTES systems are used to create optimal temperatures for end users, thus potentially meeting end-user requirements for flexible heating and cooling.

Aquifer thermal energy storage (ATES) is another variant that it uses (frequently shallow) groundwater to store heat for later use. However, heat stored in ATES systems drifts with groundwater flow, so heat must be captured downgradient before it is swept away. Shallow groundwater is frequently used for other beneficial uses, so heating or cooling this groundwater may affect others (including habitat). Compared to ATES, for RTES reservoirs, flowrates are commonly negligibly small, so heat is not swept away. RTES waters are typically of lower quality (brackish or saline), and these waters are not generally used when sufficient shallow groundwater is available.

Today's Technology Maturity Level

RTES systems are currently not in use in the United States nor are the more common ATES systems, which have been studied for many years, with widespread implementation in parts of the world.[158] ATES can be used to store hot and/or cold water, allowing flexibility in addressing diverse direct-use heating and cooling needs. Figure 18 shows the wide-range of seasonal needs for heating and cooling that can be served by ATES.

[158] Sommer et al. "Thermal performance and heat transport in aquifer thermal energy storage," *Hydrogeology Journal* (2014) 22: 263–279; DOI 10.1007/s10040-013-1066-0

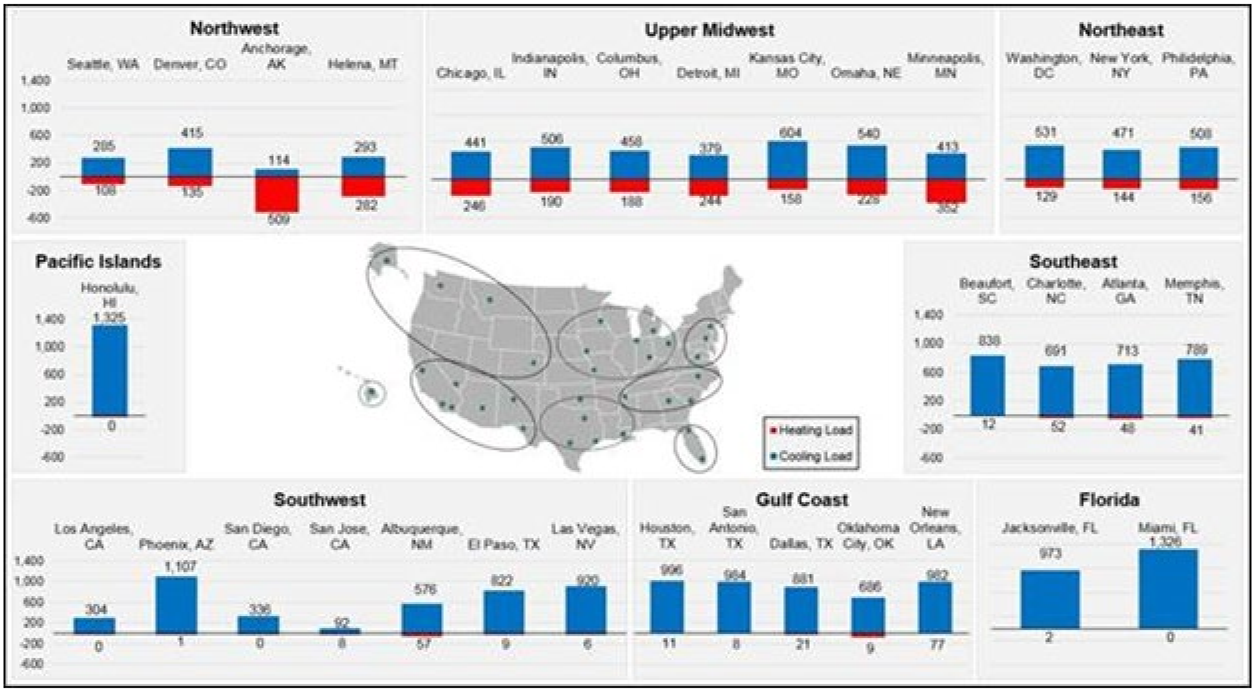

Figure 18. Map showing the estimated annual heating (red) and cooling (blue) loads.

Loads in million BTUs (1 BTU= 1055 J) for a representative 2,323 m2 two-story modern office building in selected U.S. Cities). ATES systems can be designed and operated to store hot and cool water, allowing for a flexible response to energy needs.[159]

Constraints on Architecture

The most important factors to consider when evaluating RTES efficacy are operational schedule, well spacing, the amount of summer heat stored and longevity of the system. In one study area within the Portland Basin, key identified risks , include reservoir heterogeneity (e.g., faults and fractures) and scaling (mineral precipitation) due to high temperatures involved (in this study, up to 80 C).

A base case Levelized Cost of Electricity studied by GTO researchers estimate ($34.08 per MMBtu or $116.28 per MWh) suggesting that RTES is comparable to unsubsidized solar and nuclear, but more expensive than natural gas, with additional benefits in reducing our carbon footprint and energy resiliency, particularly for critical infrastructure in the event of a natural disaster.[160]

DOE Activities

The U.S. DOE Geothermal Technologies Office invested close to $10 million in the RTES feasibility and modeling research and plans to invest approximately an additional $10 million towards engineering RTES, flexible cements, and thermal battery systems.

[159] Figure used with permission from Falta et al., 2016.

[160] Bershaw, E. et al. An Integrated Feasibility Study of Reservoir Thermal Energy Storage in Portland, Oregon; Proceedings, 45th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 10-12, 2020

Flexible Generation and Controllable Loads

Flexible generation and controllable loads include technologies, equipment, and systems capable of enhancing the flexibility of production or consumption resources. Flexible generation includes technologies that help power generation resources start and stop more quickly and easily. Flexible load technologies include both hardware and software that enable shifting of energy demand to better match generation and provide grid services, as well as integration of dispersed load with storage and behind-the-meter generation.

Flexible Loads: Generation

Integrating Energy Storage with Fossil Assets

FE funds analysis, R&D, and detailed system design projects related to integrating energy storage with fossil assets, such as coal- and gas-fired electricity generating units. Twenty-two responses to an RFI issued by FE in December 2019 showed that a range of energy storage technologies may be promising. A common characteristic is they tend to enable long-duration storage. FE is supporting several analysis projects that are reviewing the energy storage technology landscape and doing plant-level analyses to identify promising combinations of specific energy storage technologies with various asset classes. Additional modeling work focuses on the grid and market implications of deploying energy storage with fossil assets.

DOE Activity

Through the Coal FIRST initiative, FE is investing in four pre-FEED studies of energy storage integrated with coal-based power generating units that co-fire biomass and waste plastics and CCUS. The energy storage component of these designs tends to be in the 50 MW scale, with technologies such as large battery, chemical, thermal, and hydrogen storage to provide a range of services to the plant and grid. FE issued an FOA mid-FY20 with scope that included a range of fossil-fueled assets such as single-cycle gas turbines, NGCCs, and coal plants. The objective of the FOA was to integrate energy storage technologies with these assets.

Finally, FE is funding the design, construction, and testing of two 10 MW engineering-scale prototypes based on concrete thermal energy storage, which will be integrated with power plants owned by Southern Company and Dominion Energy. It has also supported various plant- and system-level modeling activities, including thermal energy storage technologies such as molten salts.

Concentrating Solar Thermal Power

Ability to Provide Functional Requirements

Concentrating solar-thermal power (CSP) technologies capture the sun's energy in the form of heat, which can be stored and used to produce electricity even when the sun is not shining. The key value proposition of CSP is its ability to enable solar electricity on demand through low-cost integration of thermal energy storage (TES). Further, CSP systems use traditional turbine-based heat engines, which are used to generate the majority of global electricity. This combination of readily scalable energy storage and proven turbine technology can provide reliable and flexible renewable electricity production. CSP technologies can also be used to collect and store heat for a variety of industrial applications, like water desalination, enhanced oil recovery, food processing, chemical production, and mineral processing.

Today's Technology Maturity Level

Approximately 7 GW of CSP has been constructed worldwide, including 1.7 GW connected to the U.S. grid and more than 400 MW in the United States that includes between 6 and 10 hours of thermal energy storage.

The majority of the CSP plants deployed today, both in the United States and worldwide, are parabolic trough systems, which were first commercially deployed in the 1980s. However, this technology is typically limited in its top operating temperature, and therefore its efficiency, to approximately 400°C. State-of-the-art CSP power plants are based on a central "power tower" that uses molten nitrate salts as both the primary heat transfer fluid (HTF) and the TES material, and operate at a temperature of approximately 565°C. The general industry transition to power towers reflects their ability to achieve higher-temperature operation and more readily integrate direct storage of molten salts, which results in both higher thermal-to-electric conversion efficiencies in the turbine and lower cost for storage, per kWh stored.

A key advantage of CSP designs is that, by placing the storage between the receiver (which collects the concentrated light and converts it to heat) and the steam turbine/generator, solar energy collection is fully decoupled from electricity generation. Moreover, the low marginal cost of additional molten salt makes it extremely cost-effective to go to very long-duration storage capacities of more than 10 hours (based on full-load turbine operation).

Constraints on Architecture

CSP production is geographically and seasonally dependent on the available solar resource. For example, a plant in the Mojave Desert with 12 hours of storage could run approximately full-time in the summer and at part-load in the winter to achieve a 70% annual capacity factor. For example, the 20 MW Gemasolar plant in Spain is designed for such performance and regularly achieves full production over 24 hours. In contrast, the 110 MW Crescent Dunes power tower in Nevada is designed for a capacity factor of 52% based on 10 hours of storage.

DOE Activity

The Solar Energy Technologies Office (SETO) supports research and development of CSP technologies. DOE is targeting the development of technologies that can raise the temperature of the heat delivered to a power cycle in a CSP plant to approximately 720°C, helping to increase the efficiency of the plant and reduce costs.[161] Reflecting the increased value of dispatchable solar, the 2030 target for CSP baseload plants with a minimum of 12 hours of energy storage is $0.05 per kWh. This target is discussed in depth in the CSP 2030 Report released by the National Renewable Energy Laboratory in January 2019.[162]

Recent SETO R&D objectives under the Gen3 CSP funding program[163] have focused on developing thermal transport systems capable of operating at temperatures greater than 700°C and integrating them with advanced, high-efficiency power cycles. Along with moving to higher temperatures, lowering

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161 Mehos, Mark, et al. *Concentrating Solar Power Gen3 Demonstration Roadmap*. NREL/TP-5500-67464. National Renewable Energy Laboratory (NREL), Golden, CO (United States), 2017.

162 https://www.nrel.gov/docs/fy19osti/71912.pdf

163 U.S. Department of Energy Solar Energy Technologies Office. FOA: https://www.energy.gov/eere/solar/funding-opportunity-announcement-generation-3-concentrating-solar-power-systems-gen3csp; Selections: https://www.energy.gov/eere/solar/generation-3-concentrating-solar-power-systems-gen3-csp

solar field costs, and integration with high-efficiency, low-cost power cycles, there are other key elements of lowering the cost of energy generation from CSP. SETO is developing these concepts through projects awarded from the Gen3 CSP funding program. Additionally, the recent SETO Fiscal Year 2018[164] and Fiscal Year 2019[165] funding programs sought CSP projects that spanned a broad domain, touching every subsystem in the plant.

Controllable Loads: Energy Storage and Buildings

Growing peak electricity demand, transmission and distribution (T&D) infrastructure constraints, and an increasing share of variable renewable electricity generation are stressing the electrical grid.[166] Residential and commercial buildings consume around 75% of the electricity generated within the United States[167] and drive a comparable share of the peak power demand. Additionally, they are expected to contribute to 70% of the growth in U.S. electricity demand through the year 2040.[168] Thermal energy storage and flexible, dispatchable electricity loads in buildings offer a unique opportunity for cost-effective, demand-side management. They can be used to reduce grid stress, creating a more resilient and reliable grid, while simultaneously lowering costs for consumers.

Within residential and commercial buildings, thermal loads including HVAC, water heating, refrigeration, and drying account for 65% and 42% respectively of annual electricity usage.[169] It is possible to power these devices using stored electricity using electrochemical batteries. If the desired end-use is a thermal load, it can be more cost-effective to store the required energy thermally in low-cost materials.[170]

Demand-side entities, such as buildings and electric vehicles, have not traditionally contributed to balancing supply and demand; however, demand-side contributions can be just as viable as supply-side counterparts. The electricity demand from buildings results from a variety of electrical loads that are primarily operated to serve the needs of occupants. However, many of these loads are flexible to some degree and can be managed to draw electricity at specific times and different levels, while still meeting productivity and comfort requirements for occupants. With proper communications and controls, buildings can manipulate energy assets within their domain to provide benefit to the grid while providing value to owners through reduced utility bills and increased resilience, among other benefits.

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164 U.S. Department of Energy Solar Energy Technologies Office. FOA: https://www.energy.gov/eere/solar/funding-opportunity-announcement-fy-2018-solar-energy-technologies-office; Selections: https://www.energy.gov/eere/solar/solar-energy-technologies-office-fiscal-year-2018-funding-program-seto-fy2018

165 U.S. Department of Energy Solar Energy Technologies Office. FOA: https://www.energy.gov/eere/solar/funding-opportunity-announcement-solar-energy-technologies-office-fiscal-year-2019; Selections: https://www.energy.gov/eere/solar/solar-energy-technologies-office-fiscal-year-2019-funding-program-seto-fy2019

166 Nadel, Steven. 2017. "Electricity Consumption and Peak Demand Scenarios for the Southeastern United States." American Council for an Energy-Efficient Economy. Washington, D.C.

167 US EIA 2019 Annual Energy Outlook 2019 with projections to 2050 Technical Report, US Energy Information Administration, Washington, DC.

168 Satre-Meloy et al. 2019. Assessing the time-sensitive impacts of energy efficiency and flexibility in the US building sector, *Environ. Res. Lett. 14* 124012.

169 Building Technologies Office, Grid-Interactive Efficient Buildings Technical Reports: Heating, Ventilation, Air Conditioning (HVAC), Water Heating, Appliances, and Commercial Refrigeration, Washington, DC.

170 Calmac, A close look at thermal versus battery energy storage for commercial applications, http://www.calmac.com/energy-storage-articles-a-close-look-at-thermal-versus-battery-energy-storage-for-commercial-applications

As part of BTO's Grid-interactive Efficient Buildings initiative, five demand flexibility modes were identified that can provide benefits to the grid, as shown in Table 16. As the primary users of electricity, leveraging storage and flexibility assets within buildings can be a more cost-effective approach to relieving stresses on the grid. There are around 125 million buildings within the United States. When aggregated across many buildings, these storage and flexibility assets can be a meaningful resource.

Table 16. Demand flexibility modes in buildings to grid services[171]

Demand-Side Management Strategies	Grid Services	Description of Building Change	Example Measures
Efficiency	Generation: Energy Generation: Capacity T&D: Non-Wires Solutions	Persistent reduction in load. Interval data may be needed for measurement and verification purposes. This is not a dispatchable service.	• Insulation Improvements • Equipment Efficiency Upgrades
Shed Load	Contingency Reserves	Load reduction for a short time to make up for a shortfall in generation.	• Flexible Loads
	Generation: Energy Generation: Capacity T&D: Non-Wires Solutions	Load reduction during peak periods in response to grid constraints or based on TOU pricing structures.	
Shift Load	Generation: Capacity T&D: Non-Wires Solutions	Load shifting from peak to off-peak periods in response to grid constraints or based on TOU pricing structures.	• Flexible Loads • Energy Storage
	Contingency Reserves	Load shift for a short time to make up for a shortfall in generation.	
	Avoid Renewable Curtailment	Load shifting to increase energy consumption at times of excess renewable generation output. This is not a dispatchable service but can be reflected through TOU pricing.	
Modulate Load	Frequency Regulation	Load modulation in real-time to closely follow grid signals. Advanced telemetry is required for output signal transmission to grid operator; must also be able to receive automatic control signal.	• Flexible Loads
	Voltage Support		
	Ramping	Load modulation to offset short-term variable renewable generation output changes.	
Generate	Ramping	Distributed generation of electricity to dispatch to the grid in response to grid signals. This requires a generator or battery and controls.	• Rooftop Solar
	Generation: Energy Generation: Capacity T&D: Non-Wires Solutions		
	Generation: Energy Generation: Capacity T&D: Non-Wires Solutions	Distributed generation of electricity for use on-site and, when available, feeding excess electricity to the grid. This is not a dispatchable service, though metered data is required.	

171 Building Technologies Office, Grid-interactive Efficient Buildings Technical Report Series: Overview of Research Challenges and Gaps, Washington, DC.

Thermostatically Controlled Loads (Flexible Loads)

Ability to Provide Functional Requirements

Thermostatically controlled loads (TCLs) are end-use appliances whose local controllers maintain temperatures within a dead-band. They have the ability to provide the demand-side management strategies of shed and shift (see Table 16). They have naturally occurring "capacitance" with respect to local temperatures and time of operation and represent a promising end-use category to engage in power system flexibility services.[172] TCLs include residential HVAC systems, electric water heaters, and refrigerators. The flexibility of TCLs for demand control comes as a result of their thermal inertia. TCLs may be viewed as a distributed energy storage resource that can be controlled with constraints imposed by an acceptable impact on end-users.[173] Varying the setting of a TCL thermostat can shift the TCL power consumption from tens of minutes to a couple of hours, depending on the appliances. If the set-point is controlled in response to the market prices or requests, the shifted TCL's power consumption can contribute to load reduction during the peak-price periods.[174]

Today's Technology Maturity Level

There is increased visibility of TCLs due to advancements in power electronics and communication capabilities enabling remote monitoring/control of TCLs. Current trends aggregate TCLs to provide certain grid services by leveraging their capability to store thermal energy and thereby achieving flexibility in power consumption. With increased renewable penetration, these advancements allow TCLs to provide several grid services such as demand response, frequency regulation, frequency response, and tracking regulation.[175] Smart thermostats for TCLs are readily available and most are part of utility rebate programs for their efficiency and demand response values. Unless they are enrolled in a demand response program, their ability to provide flexibility may be limited. Several grid-interactive water heaters are commercially available. Typical functionality is only to preheat water. However, multiple retrofit packages are available for existing water heaters that enable utility control.

Constraints on Architecture

Due to the size and population of the TCLs, each TCL cannot participate in the grid services individually. Depending on location, an aggregator is used to group these TCL devices. The aggregator acts as a mediator between the grid and the individual TCLs. It is the task of an aggregator to characterize the available flexibility for the ensemble of TCLs to provide grid services. The use of the energy storage capabilities of TCLs for grid services is constrained by inefficient measurement and verification practices and cybersecurity concerns. Advancements can also be facilitating through understanding the impact of demand flexibility use on equipment lifetime and how occupants will respond to technologies that can provide load flexibility. Increased energy usage from flexible technology could potentially lead to higher utility cost without an appropriate rate structure.

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172 Koch, Stephan, Johanna L. Mathieu, and Duncan S. Callaway. "Modeling and control of aggregated heterogeneous thermostatically controlled loads for ancillary services." In Proc. PSCC, pp. 1–7. 2011.

173 Perfumo, Cristian, Ernesto Kofman, Julio H. Braslavsky, and John K. Ward. "Load management: Model-based control of aggregate power for populations of thermostatically controlled loads." *Energy Conversion and Management 55* (2012): 36–48.

174 Lu, Ning, David P. Chassin, and Steve E. Widergren. "Modeling uncertainties in aggregated thermostatically controlled loads using a state queueing model." IEEE Transactions on Power Systems 20, no. 2 (2005): 725–733.

175 Hao, He, Borhan M. Sanandaji, Kameshwar Poolla, and Tyrone L. Vincent. "Aggregate flexibility of thermostatically controlled loads." IEEE Transactions on Power Systems 30, no. 1 (2014): 189–198.

DOE Activity

DOE's Building Technologies Office (BTO) funds TCL thermal storage characterization efforts for the use of flexible building loads to provide grid services, integrate more renewable generation, and improve building operational efficiency. BTO is also exploring the development of end-use load control hardware retrofits for use irrespective of the vendor and enable standardized control, communication, and data exchange to perform grid-responsive functions while remaining within the safety and operational constraints. A standards-based home energy management system (HEMS) that interacts with utilities and serves as a platform for deploying intelligent algorithms to execute grid-responsive functionality of a collection of residential TCLs is also being tested. The HEMS provides interoperability across multi-vendor devices and provides standard data exchange with utility systems. The program includes a standards-based grid-service dispatch and architectures for scalable aggregation of TCLs in a timely fashion to provide a variety of grid services.

Building Mass as Thermal Energy Storage (Thermal Energy Storage)

Ability to Provide Functional Requirements

Thermal mass refers to the large concrete, brick, stone, or other mass that make up the building structures and that absorb and emit significant amounts of heat. The thermal inertia from the building mass can be used to provide the demand-side management strategy of shifting load (see Table 16). Buildings with large amounts of mass have sufficient thermal inertia so that occupants will not sense short-term changes in thermostat settings. This means a building can use its HVAC system to precondition the mass of the building. When paired with proper controls, this can help the power grid match supply and demand while the building's indoor temperature remains unchanged. Building control systems can, in effect, use the thermal mass of buildings to achieve occupant comfort at lower energy costs, provide flexibility to the grid, and cost-effectively reshape load.[176]

Today's Technology Maturity Level

Intelligent building controls today can enable large. cost-effective virtual storage in buildings. They can incorporate past, current, and future temperature projections in designing the lowest-cost or highly flexible energy use strategies to achieve the desired comfort and grid service requests. The capacity to shift building energy load has been demonstrated in both commercial and residential buildings. The rise of virtual storage can help offer a faster, cheaper, and less risky strategy than hard storage options for load reshaping and renewable energy integration.

Constraints on Architecture

The impact of utilizing the virtual storage of one building would be negligible. But there are at least 5.6 million commercial buildings in the United States. Multiplied across many buildings, this effect could give energy producers and distributors vital control to maintain electricity demand and supply levels. However, business models that allow for aggregation are still fluid. Further, there is no current understanding of regulatory constraints for aggregation to exercise inter-building demand flexibility and energy exchange. The use of virtual storage for grid services are also constrained by incumbent building control systems, inefficient measurement and verification practices, lack of appropriate grid service metrics (e.g., time-varying carbon prices), lack of impact analyses (on occupants and building envelope durability), interoperability barriers, and cybersecurity concerns.

[176] https://news.engin.umich.edu/2017/09/using-university-of-michigan-buildings-as-batteries/

DOE Activity

DOE's Building Technologies Office (BTO) funds the development and deployment of retrofit control technologies (software and hardware) for engaging building loads to reduce energy consumption, reduce energy intensity, and provide grid-services.[177]

Ice and Chilled Water Thermal Energy Storage (Thermal Energy Storage)

Ability to Provide Functional Requirements

Water-based thermal energy storage systems for cooling-based applications typically consist of chilled water and ice storage installations. These technologies can help provide the demand-side management strategy of shifting load (see Table 16). These systems utilize cooling equipment in conjunction with a storage tank to house the water energy storage medium. When energy prices or environmental conditions are favorable, the cooling equipment will run. Instead of providing a cooling load to the building or other end-use, the cooling equipment will lower the temperature of the water. Later, when energy prices or environmental factors make it unfavorable to power the cooling equipment, the pre-cooled water can be used to supplement the cooling load.[178] Pumps are used to circulate a coolant between the storage medium and the delivery point of the load. Chilled water systems utilize the sensible heat capacity of the water to store energy. This translates to ~4.1 kJ/kg-water of cooling energy being stored for every degree that the temperature of the water is cooled below the cooling load delivery temperature. Alternatively, ice-based thermal energy storage systems store energy both in the sensible and latent heat capacities of water. During the freezing process, ~333 kJ/kg-water of cooling energy can be stored. Due to the stability and reversibility of the water cooling/freezing process, lifetimes on the order of 30 years can be expected from the storage medium.[179]

Today's Technology Maturity Level

Ice storage systems have been in use since the 1940s.[180] Chilled water and ice-based thermal energy storage systems have been successfully commercialized and are currently in use by multiple installations around the world.[181] Despite this, the majority of large facilities that are appropriate for chilled water and ice storage systems do not have one installed.[182]

Constraints on Architecture

Chilled water and ice-based energy storage systems typically require significant amounts of space in order to store appreciable quantities of cooling energy. Additionally, the cooling equipment's energy required to create ice or near-freezing water is typically greater than that required for direct space conditioning. This means that although building energy cost may be reduced overall energy consumption can be significantly increased with the use of ice storage systems.[183]

177 Building Technologies Office, *Grid-interactive Efficient Buildings: Overview*, Washington, DC.

178 U.S. Department of Energy, Keep It Cool with Thermal Energy Storage. https://www.nrel.gov/docs/legosti/old/20176.pdf

179 Calmac, http://www.calmac.com/

180 Federal Energy Management Program, Thermal Energy Storage for Space Cooling, https://www.osti.gov/servlets/purl/770996

181 U.S. Department of Energy, DOE OE Global Energy Storage Database. https://www.energystorageexchange.org

182 U.S. Department of Energy, A Review of Emerging Energy Storage Technologies. https://www.energy.gov/sites/prod/files/2018/06/f53/EAC_A%20Review%20of%20Emerging%20Energy%20Storage%20Technologies%20%28June%202018%29.pdf

183 Sehar et al. Impacts of ice storage on electrical energy consumptions in office buildings. *Energy and Buildings 51* (2012) p. 255.

DOE Activity

Due to the maturity of ice storage, DOE has limited R&D programs in this area. Past DOE investments such as through the Inventions and Innovations Program have helped accelerate the development of ice storage technologies.[184] DOE's Better Buildings initiative provides some educational information on ice storage systems through their solution center. This can be used by building owners and operators to better understand the benefits of ice thermal energy storage can offer their facilities.

Organic Phase Change Material Thermal Energy Storage (Thermal Energy Storage)

Ability to Provide Functional Requirements

Like water-based thermal energy storage technologies, organic phase change materials can also provide the demand-side management strategy of shifting demand (see Table 16). Phase change materials can also provide efficiency improvements which also benefit the grid.[185] One of the challenges with liquid water-to-ice-based phase change systems for higher temperature loads is the mismatch between the temperatures at which water freezes and the temperature of the load. In the case of space conditioning, the cooling equipment has to cool down to an even lower temperature to make ice than it would otherwise for space conditioning alone. This leads to excessive energy consumption. Additionally, freezing water is generally not useful for heating applications. One approach to overcome this issue is through the use of materials with phase change transition temperatures more suitable for higher temperature applications. Multiple substances have been investigated as phase change materials (PCMs) for thermal energy storage. They are generally divided into organic and inorganic materials. Organic phase change materials are further divided into paraffin waxes and non-paraffin materials. Non-paraffin organic materials typically consist of fatty acids, alcohols, esters, glycols, and other materials. Organic phase change materials typically have latent heat values in the range of 60–269 kJ/kg.[186] They have a wide range of melting temperatures and are generally non-corrosive and non-toxic.[187]

Today's Technology Maturity Level

PCMs have been widely used in a variety of industries including solar energy, industrial heat recovery, textiles, healthcare, and aerospace.[188] Organic PCMs have been used in building applications, including being embedded in envelope components. However, their low volumetric energy capacities and high combustibility are major barriers to their widespread acceptance throughout the built environment.[189]

Constraints on Architecture

Space will be required to house the storage material, or it will have to be embedded into structures of equipment. With the exception of molten metals, many PCMs suffer from poor thermal conductivity.

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184 Moore et al. The Inventions & Innovation Program: Inventors and Very Small Businesses Solving Big Energy Problems. https://www.aceee.org/files/proceedings/2004/data/papers/SS04_Panel6_Paper22.pdf

185 Daffari et al. Simulation-based optimization of PCM melting temperature to improve the energy performance in buildings. *Applied Energy 202* (2017) p. 420.

186 Khan et al. A review of performance enhancement of PCM based latent heat storage system within the context of materials, thermal stability, and compatibility. *Energy Conversion and Management 115* (2016) p. 132.

187 Baetens et al. Phase change materials for building applications: A state-of-the-art review. *Energy and Buildings 42* (2010) p. 1361.

188 Huang et al. Morphological characterization and applications of phase change materials in thermal energy storage: A review. *Renewable and Sustainable Energy Reviews 72* (2017) p. 128.

189 Abuelnuor et al. Improving indoor thermal comfort by using phase change materials: A review. *International Journal of Energy Research 42* (2018) p. 2084.

With values in the range of 0.2 W/m-K for paraffin waxes,[190] charging and discharging of the storage medium can be hindered. Paraffins waxes are also expensive, and most are byproducts of or obtained through petroleum refining. Additionally, paraffin waxes undergo large volume changes during phase transitions which have to be considered during design.[191] Various approaches have been taken to mitigate some of these challenges including the use of fillers to boost thermal conductivity[192] and encapsulation to reduce leaking during the phase change process,[193] but these come at an increased cost.

DOE Activity

The Building Technologies Office has active R&D looking into bio-based, organic phase change materials. This work is focused on refining their properties and improving their manufacturing process for incorporation into building equipment and envelopes. Additionally, the Advanced Manufacturing Office is pursuing research focused on the thermal storage for industrially relevant processes and applications. ARPA-E has also sponsored work looking at the use of PCMs incorporated into thermal systems.

Salt Hydrate Thermal Energy Storage (Thermal Energy Storage)

Ability to Provide Functional Requirements

Inorganic PCMs typically consist of water, hydrated salts, and molten salts or alloys. Salt hydrates are materials that undergo a hydration/dehydration phase transition process which can be used to store thermal energy. Like organic-based phase change materials, salt hydrate based thermal energy storage can support the grid through load shifting as well as efficiency improvements (see Table 16). They have gained attention as promising thermal energy storage materials due to their low cost and high thermal conductivity, relative to many organic PCMs.[194] Compared to organic PCMs, inorganic PCM typically have higher volumetric and gravimetric densities leading to high latent heats in the range of 86–328 kJ/kg.[195] Salt hydrates are generally limited to applications below 100°C.

Today's Technology Maturity Level

Salt hydrates are actively investigated for thermal energy storage applications. Work has been done looking into their integration into water heating, building envelope, refrigeration, and air conditioning systems.[196] A number of hydrates are commercially available; however, more work to address technical challenges can enable them to be used as effective thermal energy storage solutions.[197]

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190 Huang et al. Morphological characterization and applications of phase change materials in thermal energy storage: A review. *Renewable and Sustainable Energy Reviews 72* (2017) p. 128.

191 Baetens et al. Phase change materials for building applications: A state-of-the-art review. *Energy and Buildings 42* (2010) p. 1361.

192 Lin et al. Review on thermal conductivity enhancement, thermal properties and applications of phase change materials in thermal energy storage. *Renewable and Sustainable Energy Reviews 82* (2018) p. 2730.

193 Baetens et al. Phase change materials for building applications: A state-of-the-art review. *Energy and Buildings* 42 (2010) p. 1361.

194 Cabeza et al. Materials used as PCM in thermal energy storage in buildings: A review. *Renewable and Sustainable Energy Reviews 15* (2011) p. 1675.

195 Khan et al. A review of performance enhancement of PCM based latent heat storage system within the context of materials, thermal stability, and compatibility. *Energy Conversion and Management 115* (2016) p. 132.

196 Xie et al. Inorganic Salt Hydrate for Thermal Energy Storage. *Applied Sciences 7* (2017) p. 1317.

197 Hirschey et al. Review of Inorganic Salt Hydrates with Phase Change Temperature in Range of 5°C to 60°C and Material Cost Comparison with Common Waxes. 5th International High Performance Buildings Conference.

Constraints on Architecture

Space will be required to house the storage material, or it will have to be embedded into structures of equipment. Similar to organic PCMs, salt hydrates also suffer from low thermal conductivities in the range of 0.7 W/m-K.[198] Many technical challenges remain for salt hydrate systems, including addressing supercooling, corrosiveness, and phase segregation.[199] Supercooling occurs when the PCM has to be cooled well below the transition temperature before phase transition begins. Hysteresis occurs when there is a difference between the melting and solidification temperatures.[200] Both supercooling and hysteresis lead to inefficiencies in the energy storage process. During the melting process of salt hydrates, some anhydrous salt can settle out of the solution and fail to recombine upon refreezing. This incongruent melting leads to phase segregation and can degrade performance over time.[201] Additionally, incompatibilities between various salt hydrates and storage vessels can lead to corrosion and containment issues.

DOE Activity

The Building Technologies Office is funding work on salt hydrates to reduce excessive subcooling, address incongruent melting and phase segregation, reduce corrosiveness, efficiently achieve microencapsulation, and incorporate into building equipment and envelopes for heating and cooling loads. Additionally, the Advanced Manufacturing Office is pursuing research focused on the thermal storage for industrially relevant processes and applications relevant to salt hydrate operating conditions. ARPA-E has also invested in projects to improve thermal storage capabilities, which have included work on salt hydrates.

Thermochemical Reaction Thermal Energy Storage (Thermal Energy Storage)

Ability to Provide Functional Requirements

In addition to storing thermal energy in sensible and latent forms, thermal energy can be stored in chemical bonds. Thermochemical energy storage methods have attracted attention for their high energy densities, potentially much higher than PCMs, and low losses during storage. They have the ability to provide the demand-side management strategies of shifting load and efficiency improvements (see Table 16). These storage methods are based on a reversible chemical reaction. As heat is input into the storage medium, an endothermic reaction takes place. Alternatively, when the reverse exothermic reaction takes place, heat is released. By separating the products of the reaction, the reverse reactions can be prevented from spontaneously occurring. This means that thermal energy could be stored for long periods of time (potentially seasons) with negligible self-discharge. A variety of reaction

198 Huang et al. Morphological characterization and applications of phase change materials in thermal energy storage: A review. *Renewable and Sustainable Energy Reviews 72* (2017) p. 128.

199 Khan et al. A review of performance enhancement of PCM based latent heat storage system within the context of materials, thermal stability, and compatibility. *Energy Conversion and Management* 115 (2016) p. 132.

200 Hsu et al. Thermal hysteresis in phase-change materials: Encapsulated metal alloy core-shell microparticles. *Nano Energy 51* (2018) p. 563.

201 Hirschey et al. Review of Inorganic Salt Hydrates with Phase Change Temperature in Range of 5°C to 60°C and Material Cost Comparison with Common Waxes. 5th International High Performance Buildings Conference.

mechanisms have been proposed for thermochemical energy storage, including sorption-based and redox reactions.[202,203]

Today's Technology Maturity Level

Relative to sensible and latent thermal energy storage, research in thermochemical energy storage is still in its infancy. Numerous applications have been investigated for building, solar thermal, and industrial requirements. There have been pilot studies on the use of thermochemical energy storage for the transport of waste heat from industrial processes[204] as well as storing heat for concentrated solar thermal applications.[205]

Constraints on Architecture

Though less than that required for latent energy storage systems, space will still be required to house the storage material. Thermochemical reactions have a number of advantages over sensible and latent forms, but several technical challenges remain before they can achieve commercial viability. Sorption-based systems may suffer from low adsorbent/absorbent holding capacity and structural deterioration. Other opportunities include new materials that have structural strength and good sorption kinetics, and are low cost and practical to produce.[206] For all thermochemical reactions, cycle stability and reactor design, including heat transfer performance as well as system integration, are crucial obstacles to address to further the practicality of these systems.[207]

DOE Activity

The Building Technologies Office is funding work looking at advances to optimize the operating requirements of thermochemical storage methods, including but not limited to, operating temperatures, multi-cycling efficiency, and material cost. Additionally, the Advanced Manufacturing Office is pursuing research focused on the thermal storage for industrially relevant processes and applications including thermochemical approaches. The Solar Energy Technologies Office is also looking into thermochemical methods of energy storage for concentrated solar thermal energy systems. Investments by ARPA-E have looked at developing revolutionary, cost-effective ways to store thermal energy including converting heat into fuel.

Desiccant Energy Storage (Thermal Energy Storage)

Ability to Provide Functional Requirements

Thermal energy storage is primarily focused on the release and capture of heat. In building applications, humidity, in conjunction with temperature, contributes to the occupant comfort. The most common means of humidity control in buildings is cooling air below its dew point in order to condense water out

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202 Solé et al. State of the art on gas–solid thermochemical energy storage systems and reactors for building applications. *Renewable and Sustainable Energy Reviews 47* (2015) p. 386.

203 Prieto et al. Review of technology: Thermochemical energy storage for concentrated solar power plants. *Renewable and Sustainable Energy Reviews 60* (2016) p. 909.

204 Jarimi et al. Review on the recent progress of thermochemical materials and processes for solar thermal energy storage and industrial waste heat recovery. *International Journal of Low-Carbon Technologies 14* (2019) p. 44.

205 Andrew et al. Demonstration of High-Temperature Calcium-Based Thermochemical Energy Storage System for use with Concentrating Solar Power Facilities. Technical Report, doi:10.2172/1523643.

206 Jarimi et al. Review on the recent progress of thermochemical materials and processes for solar thermal energy storage and industrial waste heat recovery. *International Journal of Low-Carbon Technologies 14* (2019) p. 44.

207 Chen et al. State of the art on the high-temperature thermochemical energy storage systems. *Energy Conversion and Management 177* (2018) p. 792.

of the air. In this way, space conditioning loads can be divided into sensible loads (changing the temperature of the air) and latent loads (changing the humidity of the air). Desiccant materials have the ability to dehumidify by directly absorbing water vapor into their structure. They can be used to provide the demand-side management strategies of shifting load and efficiency improvements (see Table 16). Once saturated, these materials can reject this water by undergoing a regeneration process. When isolated, these desiccants can store dehumidification space conditioning capacity and can be used on demand. Depending on how the desiccant is regenerated, efficiency benefits are also possible. In addition to occupant comfort in building, desiccants can also prove useful for a host of drying processes in industry and agriculture. Process drying typically involves the use of heated air to drive off moisture.

Today's Technology Maturity Level

Desiccant-based systems have been proposed for multiple applications ranging from drying processes to space conditioning. Some studies have looked into the storage of regenerated desiccant material for use during peak energy use times,[208,209] but the majority of work surrounding desiccant systems has focused on continuous-use operations.

Constraints on Architecture

Space is required to store desiccant materials while they await use for dehumidification. In general, liquid desiccants are easier to store and deploy when needed than solid desiccants. Some challenges facing liquid desiccant systems are reverse dehumidification, corrosion, desiccant carryover, and crystallization.[210] If the desiccant material is not sufficiently regenerated, then it can re-humidify the air. Membranes are necessary to prevent salt transfer into the product stream and plastics are typically required to inhibit corrosion. Depending on the composition and temperature of the desiccant, crystallization of salts can occur, which can reduce the effectiveness of the desiccant.

DOE Activity

The Building Technologies Office has funded work that looks at the integration of desiccant energy storage to reduce peak space conditioning loads. Additionally, the Advanced Manufacturing Office is pursuing research focused on improving industrial and process drying. ARPA-E has funded work into advanced desiccant systems which could potentially feed into future storage systems.

Thermal Energy Storage for Controllable Loads

Note that general concepts related to Reservoir Thermal Energy Storage (RTES) are included in the "Chemical and Thermal Energy Storage" section of this Appendix. This section summarizes how RTES applications can be used to provide flexible, always-on capacity to support peak utility loads.

Ability to Provide Functional Requirements

High-temperature RTES systems are a promising category of RTES technology being developed to store high-temperature thermal energy from power plants in synthetic subsurface reservoirs for later use by a power plant to provide electrons back to the utility, or to provide direct thermal energy for use at or near the reservoir to directly heat and cool end uses. This technology cuts across all categories of thermal energy storage, flexible generation, and bidirectional energy storage.

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208 Ally, Novel Solar Absorption Cooling System to Reduce Peak Loads. BTO 2018 Peer Review.

209 Miller, Energy storage via desiccants for food/agricultural applications. *Energy in Agriculture 2* (1983) p. 341.

210 Sahlot et al. Desiccant cooling systems: a review. *International Journal of Low-Carbon Technologies 11* (2016) p. 489.

Borehole Thermal Energy Storage (BTES) uses a ground formation as the storage medium and exchanges heat with the ground through a group of vertical borehole heat exchangers. The vertical borehole lengths are usually in the range of 30 to 100 meters with approximately 3- to 4-meter separations.[211] In the borehole, heat is typically exchanged through double or single U-pipes or concentric pipes. The pipe is commonly made with high-density polyethylene. The heat transfer fluid in the tubes is water or an aqueous solution of anti-freeze. Recent studies have pointed out that increasing the depths of the borehole may lead to a higher temperature at the bottom of the borehole, making it more suitable for storing heat.[212,213] The energy storage capacity and efficiency of a BTES are affected by geological formation, geometry and layout of the bore field, temperature, and duration of the thermal energy storage, etc.

Today's Technology Maturity Level

Figure 19 shows a schematic of the high-temperature RTES concept with flexible load applications. The main components include the power block, heat source, and RTES reservoir. During the charging cycle, the heat source is used to heat the fluid pumped from the cold wells to the hot wells. During the discharging cycle, heated fluid from the hot wells is extracted and sent to the power block for producing power. The cooled fluid exiting the power block is sent to the cold wells.

Wendt et al. (2019) and McLing et al. (2019) provide a detailed description of RTES reservoir configuration, heat source requirements, heat recovery power cycle configuration, and operating principles.[214,215]

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211 Schmidt T, Mangold D, Muller-Steinhagen H. Seasonal thermal energy storage in Germany. ISES Solar World Congress, Goteborg, Sweden, 2003.

212 Guillaume, F. (2011). Analysis of a Novel Pipe in Pipe Coaxial Borehole Heat Exchanger. Ph. D. thesis, KTH School of Industrial Engineering and Management, Stockholm, Sweden.

213 Guo, H. and F. Meggers (2019). Charging and Discharging a Coaxial Borehole Heat Exchanger as a Battery. Building Simulation Conference, 2019.

214 Wendt, D., H. Huang, G. Zhu, P. Sharan, K. Kitz, S. Green, J. McLennan, J. McTigue, and G. Neupane. 2019. Flexible Geothermal Power Generation utilizing Geologic Thermal Energy Storage: Seedling Project Final Report, Idaho National Laboratory, INL/EXT-19-53931.

215 McLing T. L., D. Wendt, P. Dobson, C. Doughty, N. Spycher, D. Roberson, and J. McLaughlin. 2019. Dynamic Earth Energy Storage: Terawatt-Year, Grid-Scale Energy Storage using Planet Earth as a Thermal Battery (GeoTES): Seedling Project Final Report. Idaho National Laboratory, INL/EXT-19-53932.

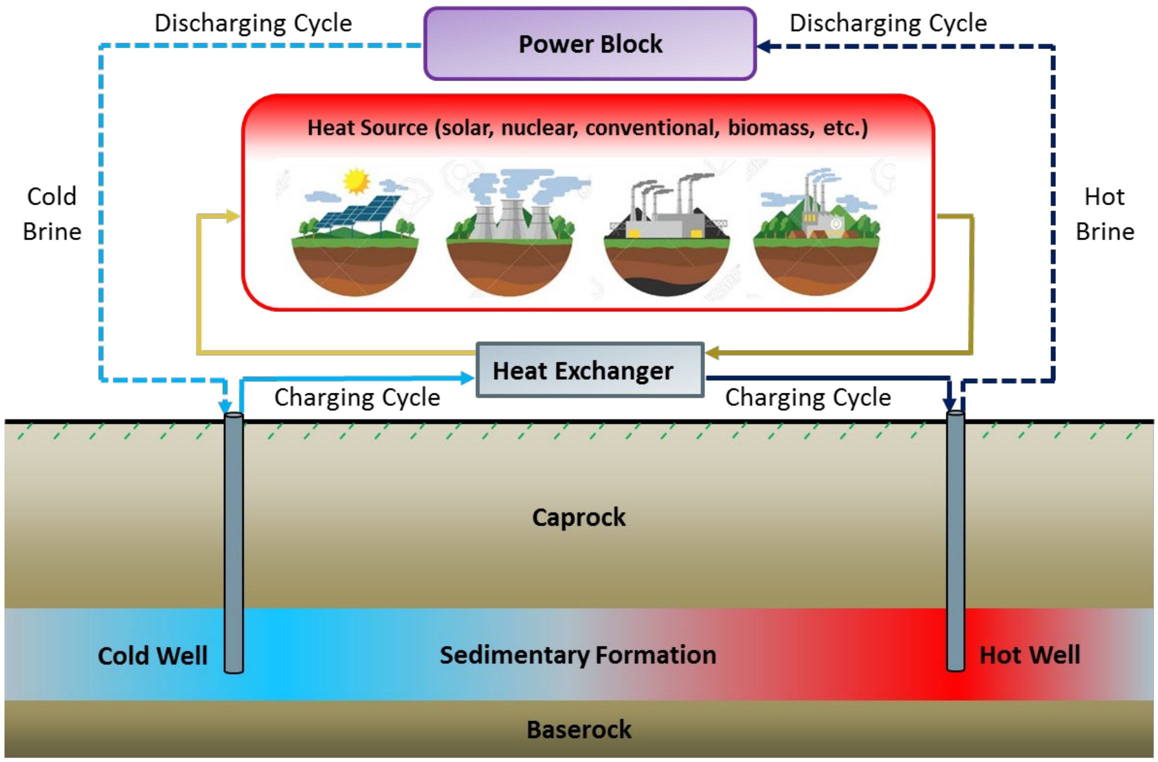

Figure 19. A conceptual synthetic RTES agnostic to the source of heat supplied for storage

High-temperature RTES installations are not limited to locations with an existing geothermal resource, and since the heat is provided from an external source, the *productivity of the thermal resource does not decline over time*. Because heat is added and recovered from the subsurface via the hot wells in a RTES system, the hot and cold wells can be closely spaced without risking resource temperature decline as a result of extracting the natively available heat. The generally higher permeabilities associated with sedimentary formations, combined with the relatively shallow depths, would lead to low parasitic pumping power requirements for RTES systems.

The recently developed Dual Purpose Underground Thermal Battery (DPUTB), illustrated in Figure 20, is a new type of BTES, which can be installed in shallower boreholes (less than 6 meters deep). Different from other underground thermal energy storage technologies (used for seasonal storage), DPUTB can provide diurnal bidirectional thermal energy storage and thus enable flexible electric load at buildings, which is becoming more important to mitigate the “duck curve” effect resulting from the growing, highly variable renewable power supply. DPUTB integrates a ground heat exchanger with thermal energy storage. It is capable of storing cooling or heating energy in the core of the tank (an insulated inner tank), and it uses the outer annular body of the tank to exchange heat with the surrounding ground formation. The thermal capacities in both the inner tank and the annulus of the DPUTB are increased utilizing phase change materials (PCMs). The large thermal capacity of the DPUTB offers a wide range of opportunities, including trimming or shifting electric demand, which is very valuable in areas that have demand-based electric rates. DPUTB can provide direct cooling/heating with little electricity consumption for a short period (a few hours), which could significantly reduce electric demand during peak hours.

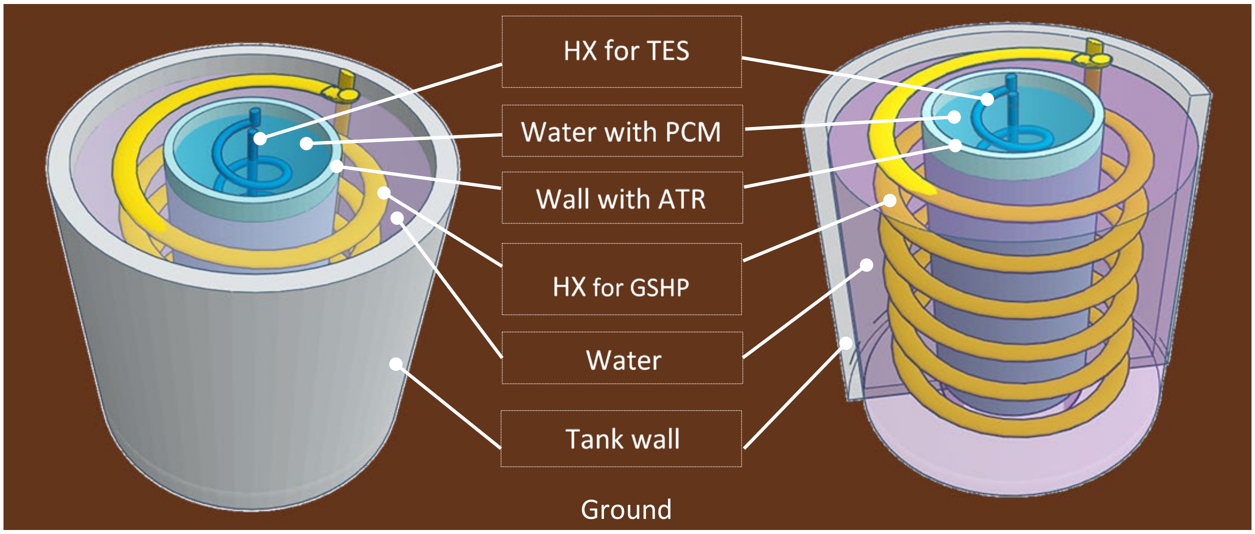

Figure 20. Schematic of the dual-purpose underground thermal battery (DPUTB).[216]

BTES systems have been used in Canada, China, the United States, and other countries in recent years. For example, Drake Landing Solar Community (DLSC) in Canada, built in 2006, is the first large-scale BTES designed as a part of a solar community. DLSC has achieved a 97% solar fraction after five years of operation. A BTES containing 144 boreholes of 35-meter depth installed in 24 parallel circuits is used as seasonal thermal storage. Figure 21 depicts the DLSC simplified system schematic.[217]

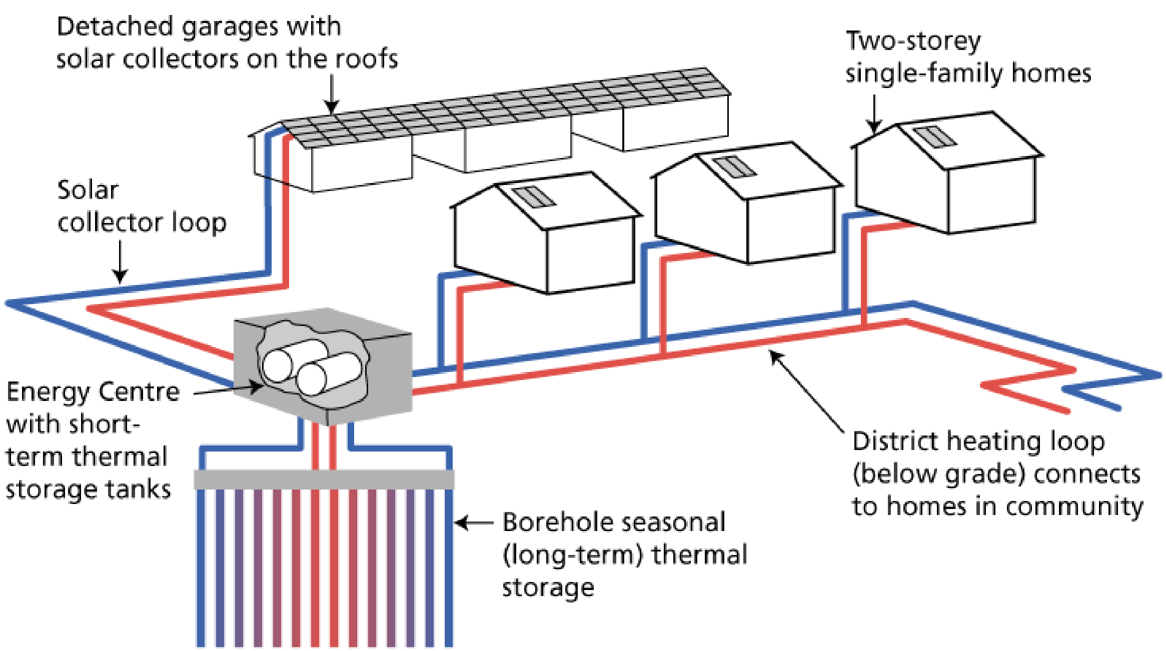

Figure 21. A simplified schematic of the Drake Landing Solar Community (DLSC) in Canada

216 Patent pending, DOE S# S-138,992

217 Sibbitt B, McClenahan D, Djebbar R, Thornton J, Kokko J, Wong B, et al. The performance of a high solar fraction seasonal storage district heating system—five years in operation. *Energy Procedia 2011*; 30:856–65.

Constraints on Architecture

The major challenge of high-temperature RTES is the coupled fluid and heat flow in the storage reservoir. Preliminary modeling results suggest that with the highly saline water (>35,000 mg/L) composition considered (and likely to be encountered), increasing RTES temperature could lead to scaling in both the surface and equipment installed to heat the extracted water and in the geologic formations around injection wells. Further studies could assess (1) the scaling potential of other, possibly more diluted formation waters or waters from different geological and hydrological settings, (2) the use of anti-scalants and their potential effects on the economics of the RTES operation, and (3) extraction/injection scenarios that minimize the scaling potential.

Other BTES opportunities include improvements to reduce heat loss and reduce costs. Possible solutions include optimization of the borehole field layout and leveraging of the Earth's natural geothermal gradient.

DOE Activities

DOE's Geothermal Technologies Office invested close to $10 million in RTES feasibility and modeling research and plans to invest approximately an additional $10 million toward engineering RTES, flexible cements, and thermal battery systems.

Thermal-Shock Resistant Cement for Heat Storage

Both flexible and insulating cement performance under hydrothermal conditions are being developed to address geothermal power plant ramping (up and down) as well as thermal storage, which has not been researched to date and may significantly decrease the losses and extend the life cycle of the wells for 20 to 40 years. Currently used well cements are not adapted for thermal shocks and are not designed to provide well durability or prevent heat losses. The objectives of the cement under development include both.

Ability to Provide Functional Requirements

Geothermal energy may offer both daily and seasonal stabilization of grid operations using underground natural geothermal energy storage systems alone or in combination with solar energy. Long-term reliable performance of such systems will depend on the wellbore integrity of the geothermal wells.

Constraints on Architecture

One of the main stresses compromising well performance is related to the frequent and possibly significant (especially in the case of combined solar-geothermal solutions) temperature variations caused by injections of very hot (from solar heat recovery for storage) or cold (cold fluids injections for geothermal heat recoveries) fluids. The cycles may be of short (daily) or longer (seasonal) frequencies. During the frequent thermal cycling the cement sheath repeatedly undergoes thermal stresses by thermal expansion (microcrack development in sheath by compressive stress) and cool contraction of casing (micro-annulus development between the sheath and casing by tensile stress).

DOE Activities

Flexible cement R&D is included in GTO's geothermal advanced energy storage portfolio and is focused on repeated stress conditions, subjecting cement sheath and bulk cement to multiple stress cycles, while monitoring dimensional stability of cement, cement's coefficient of thermal expansion, and shrinkage upon exposure to cold fluids. In addition, the research is focused on monitored changes in micro properties (phase transitions) of cement sheath and bulk cement to define physicochemical factors governing stability and degradation of the cement.

Crosscutting

Crosscutting technologies such as Power Electronics (PE) include technologies capable of electricity control and conversion. PE refers to the broad set of technologies (e.g., materials, components, subsystems, and systems) necessary for the control and conversion of electricity. A *power electronic system* (PES) is a self-contained, fully functional collection of hardware and software that safely and efficiently converts current-type (e.g., AC to DC, DC to AC), voltage (e.g., DC to DC), frequency (e.g., AC to AC), or any combination thereof, and conditions electric power according to application-specific requirements.

Power Electronics

Power Electronic Systems

Ability to Provide Functional Requirements

Power Electronic Systems (PES) are a key enabling technology for Energy Storage Systems (ESS). Converters provide bidirectional functionality, current conversion, and voltage conversion. PES provide the control capability for ESS to provide grid services and enable the integration of energy storage technologies with other sources and components, providing hybrid solutions for grid applications. Power electronic converter topologies can assist in scaling, voltage regulation, as well as reducing ESS costs, and increasing its lifetime. Modular and scalable PES with interoperable hardware and software interfaces provide integration solutions not only for Batter Energy Storage Systems (BESS) but also for hydrogen energy storage systems and other energy storage technologies.

Today’s Technology Maturity Level

The integration of PES and ESS is a time consuming and costly process. PES design and integration is often unique to a particular application, posing a key challenge on cost reduction and reduction of lead times. Modular plug-and-play designs for PES and ESS integration can be important tools in reducing costs. Future PES and ESS integration, designed holistically with standardized, modular, scalable systems architecture framework, will provide advantages over a component based solution and a “one architecture fits all” mindset to provide the best solution for a given Use Case scenario.

Constraints on Architecture

The voltage rating of semiconductor switches is a key parameter in sub-systems design. Current trends of energy storage technologies indicate the possibility of increased voltage ranges in the future, resulting in increased voltage stress on power electronics sub-system components such as breakers, connectors, insulation for magnetic components, and capacitors. In order to meet future systems requirements, R&D of medium voltage power electronics interfaces could expand useful applications since the currently available medium voltage devices are not available in higher ratings.

Thermal management is critical to the reliable operation of PES. Other R&D opportunities on thermal management solutions include new materials, more compact mechanical components, tighter integration with passives and packaging, and understanding broader system interactions.

DOE Activities

Several offices and programs across DOE are actively investing in power electronics for different applications. The technical challenges and the portfolio of R&D activities for each application differ based on the current state of the art and the availability of commercial solutions. The percentages in Figure 22 reflect an estimated "level of effort" of the various DOE programs across the R&D hierarchy. Modeling and simulation, controls and interactions, and other forms of PE-related research topics aside from development of the core hardware are outside the scope of this document and were not included in the data collection. Voltage ratings are also provided to indicate where the various program technologies are deployed in the electric power system.

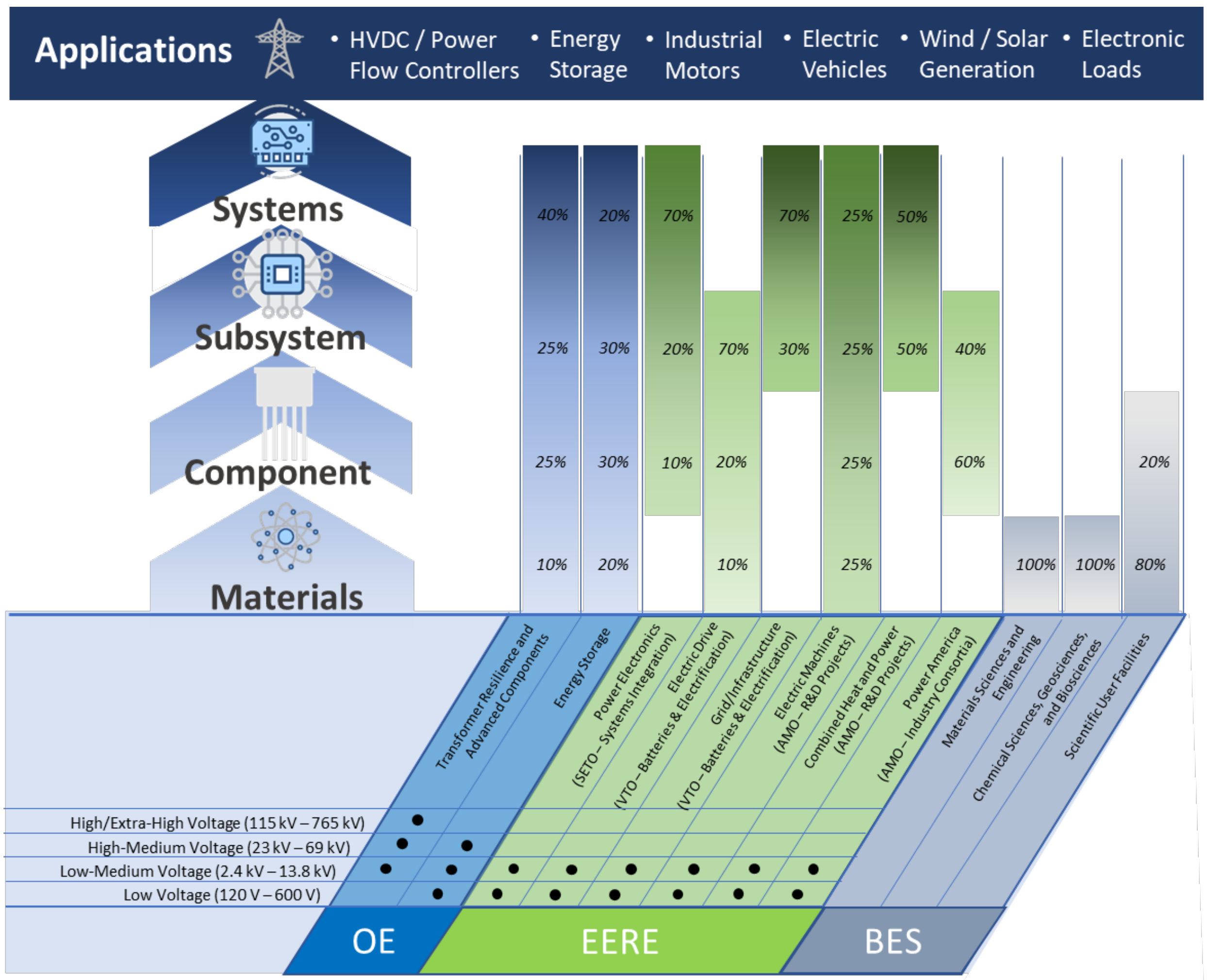

Figure 22. Summary of relevant power electronic programs at DOE

OE: Office of Electricity; EERE: Office of Energy Efficiency and Renewable Energy; BES: Basic Energy Sciences

Appendix 4: DOE Energy Storage Policy and Valuation Activities

Working with stakeholders and experts at the National Labs, the Policy and Valuation Track identified four key issue areas (resilience, power system operations, energy system planning, and transportation and cross-sectoral) and four foundational needs (cost and performance data, valuation methodologies, improved tools, and markets and utility operations information). The policy and valuation foundational needs are intended to intersect with key issue areas, e.g., storage technology cost and performance data, novel valuation methodologies, improved tools, and an understanding of market and utility operations are required to answer questions on how storage can improve system or end-use resilience. This Appendix maps ongoing DOE activities onto the four key energy storage policy and valuation issue areas and the four policy and valuation foundational needs and will be used as a baseline to start coordinating policy and valuation related storage activities inside DOE and at the National Labs. Because storage competes with, and is impacted by, other technologies in the energy system, some activities included may not directly focus on energy storage but are crucial to answer pressing storage policy and valuation issues. This list will be updated as new activities are identified and initiated.

Key Energy Storage Policy and Valuation Issue Areas

Resilience

- **North American Energy Resiliency Model (NAERM)** (multiple labs) [OE, EERE, NE, FE] – A comprehensive resilience modeling system for the North American energy sector infrastructure, which includes the United States and interconnected portions of Canada and Mexico.
- **HydroWIRES Topic C: Quantifying Reliability and Resilience** (ORNL) [EERE] – Develop a taxonomy of power system events and conditions; determine what capabilities or grid services are needed to respond to the event; examine hydropower's capabilities to provide those services; and develop some illustrative case studies that showcase hydropower. The water storage capabilities of hydropower facilities are what enables hydro to provide the necessary grid services and flexibility/response.
- **Interruption Cost Estimate (ICE) Calculator** (LBNL) [OE] – A tool designed for electric reliability planners at utilities, government organizations, or other entities that are interested in estimating interruption costs and the benefits associated with reliability improvements. The ICE Calculator is intended for estimating the costs of power interruptions lasting 24 hours or less. It can be used to monetize the benefits of storage, but only if the technology can be shown to avoid power interruptions lasting 24 hours or less.
- **Reconfigurable and Resilient Operation of Network-Controlled Building Microgrids with Solar Integration** (ANL) [EERE] – Multi-timescale (pre/post outage) optimization framework to facilitate the benefits of distributed solar energy in resilience improvement of distribution grid against disastrous events and ensure a 5-day islanded operation supported by solar, storage, and other DERs (solar+X).
- **GMLC Laboratories Valuation Analysis Team** (multiple labs) [GMLC] – This project involves developing and implementing a resilience valuation framework at up to six resilient distribution

systems. It will use field and simulation data detailing power interruptions pre- and post-deployment; may involve conducting surveys and running regional economic models.

- **Connected Communities** (ORNL) [OE] – First of its kind microgrid deployment in the Southeast. Two greenfield microgrid deployments with Southern Company. ORNL completed development of building controls on VOLTTRON platform.
- **Microgrid Assisted Design for Remote Area (MADRA)** (ORNL) [OE] – Integration of modeling systems to provide open source microgrid analysis platform for remote off-grid applications.
- **Novel Ground Level Integrated Diverse Energy Storage (GLIDES) Technology for Grid Resiliency** (ORNL) [OE] – 1) characterization of the power generation of GLIDES and (2) developing the power conditioning systems for GLIDES to become grid-ready and a dispatchable energy storage system.
- **Integrated DMS** (ANL) [OE] – Demonstrate the interaction of microgrid energy management systems through field trials with an integrated DMS to support reliability and resiliency to both microgrids and distribution grid in presence of DERs.
- **Supervisory Parameter Adjustment Distribution Energy Storage (SPADES)** (LBNL) [OE, CESER] – Develop the methodology and tools allowing Energy Storage Systems (ESS) to automatically reconfigure themselves to counteract cyberattacks against both the ESS control system directly and indirectly through the electric distribution grid.
- **REopt Lite** (NREL) [EERE] – REopt Lite optimally sizes and dispatches hybrid (PV, storage, wind, CHP, and back-up generation) behind-the-meter energy systems to sustain critical loads during grid outages while maximizing the grid-connected economic benefit. The free, publicly available webtool allows users to consider the impact of assigning a value of lost load on the optimal solution.

Power System Operations

- **Solar-to-Grid** (LBNL) [EERE] – Annual data analysis to track and understand the impact of growing solar penetration on the U.S. power system. Project includes analysis that quantifies how solar changes the motivation to invest in complementary flexible resources such as storage, demand response, and flexible thermal plants.
- **Modular HF Isolated Medium Voltage String Inverters Enable a New Paradigm for Utility Scale Solar Projects** (ORNL) [EERE] – Develop and validate new inverter to significantly reduce the balance-of-system costs in larger commercial and utility-scale PV or PV + battery farms, and realize higher-value propositions such as dispatchability and dynamic grid support.
- **CSP Real-Time Operations Optimization Software** (NREL) [EERE] – The project targets several key objectives, including: (1) to address the core challenge of understanding and optimizing the trade-off between system availability, O&M costs, and operation schedules with a goal of improving long-term net revenue; (2) to reduce solve time for dispatch optimization problem to significantly less than the plant operator decision time span; and (3) to achieve adoption of the platform at an operating facility.
- **Dynamic Building Load Control to Facilitate High Penetrations of Solar Technologies** (ORNL) [EERE] Develop, demonstrate, and validate a sensing and control mechanism for using loads to mitigate the variable PV generation to reduce two-way power flow and mitigate voltage instability on distribution level circuits.

- **HydroWIRES Topic A: Improving Hydropower Benefits by Linking Environmental and Power System Tradeoffs Through Flow Release Decisions** (ORNL, ANL) [EERE] – The goals of this project are to clarify, classify, and standardize the study, specification, and implementation of linkages between power system and environmental outcomes that are impacted by river flow that create value propositions attractive to a diverse body of hydropower stakeholders.
- **HydroWIRES Topic D: Addressing Barriers to Energy Storage in Transmission Planning and Operations** (PNNL, ANL) [EERE] – This project will identify those barriers, create a proposed participation model for PSH to provide transmission and market functions, and conduct a techno-economic analysis of PSH that fully quantifies its technical capability and economic value as a transmission asset.
- **National Lab Testing Network** (multiple labs) [GMLC] – Accelerate grid modernization by improving access to National Lab testing infrastructure for grid devices and systems, and related models and resources. Enable National Labs to more effectively drive innovation in the grid space.
- **Prototype Secondary Use Energy Storage System and Value Proposition** (ORNL) [OE] – Full prototype development (100kW and higher), cost analysis for a secondary use energy storage system. Testing Use Cases for secondary use ABB/GM system and considering value propositions.
- **Complete System-Level Microgrid Integrated Controls (CSEISMIC)** (ORNL) [OE] – Open-source microgrid controller to reduce cost and accelerate adoption of advanced controls. Integrating buildings, vehicles, renewables, and energy storage systems.
- **Efficient Buildings: A Risk-Based Framework for Dynamic Assessment and Prioritization of Flexible Building Loads** (LBNL) [EERE] – This project is developing decision algorithms that guide commercial building operators in responding to demand response (DR) calls from the electric grid, with the goal of informing next-generation DR participation that is risk-aware, adaptive, and driven by operator preferences.
- **Responsive Residential Loads Providing Grid Services** (ORNL) [EERE] – Perform field evaluation for utility-integrated demand-side management solution using open standards and open source reference platforms with utilities in the Southeast.
- **Techno-Economic Optimization of Advanced Energy Plants with Integrated Thermal, Mechanical, and Electro-Chemical Storage** (NETL) [FE] – West Virginia University Research Corporation will evaluate the transient response to various system concepts that minimize the levelized cost of electricity of thermal, chemical, mechanical, and electro-chemical storage technologies.
- **H2@Scale CRADAs** (NREL, INL) [EERE, NE] – Three CRADAs (#1 with Southern Company, Xcel Energy, and Exelon; #2 with Exelon; #3 with Xcel Energy) are focused on identifying the opportunities to improve the economics of nuclear and renewable generation by producing hydrogen when the electricity price is low.
- **H2@Scale Long-Duration CRADAs** (NREL/EPRI) [EERE, NE] – This research will provide an understanding for how utility-scale long duration energy storage and flexible load can be used to support the grid by providing balancing services, providing ancillary services, and reducing renewable curtailment from excess generation. Importantly, this will provide a more complete cost-benefit analysis for grid-integrated hydrogen technology deployment that will be used to

understand the cost competitiveness of long duration energy storage and flexible load resources.

Energy System Planning

- **High Solar Penetration Scenario Analysis** (NREL) [EERE] – Identify challenges to increased deployment of PV and find synergies with battery storage. Objectives: 1) PV and Storage to provide grid services during times of extreme weather; 2) Drivers of curtailment with and without storage; 3) Value of solar as a grid resource with different storage configurations.
- **Renewable Hybrid Energy Systems** (NREL, LBNL) [EERE] – Much of the focus is on PV + batteries, but there are a number of combinations. However, there has been little detailed exploration of the near- and long-term economic feasibility of renewable-storage hybrids, or their potential contribution to the grid compared to “stand alone” renewable generators. In response to these research needs, this project will: 1) develop a hybrid taxonomy; 2) assess current hybrid value; and 3) estimate hybrid deployment and value in potential future scenarios
- **Load Curve Analysis** (LBNL) [OE] – This project will model aggregate electricity demand of a group of single-family residential buildings under various DER deployment scenarios (including behind-the-meter storage), generating daily and seasonal load shapes to inform future electricity delivery planning.
- **National Storage Economics Map** (NREL) [EERE] – National analysis of behind-the-meter battery storage economics to inform economically feasible projects for federal agencies.
- **H2@Scale Analysis Project** (NREL) [EERE] – The H2@Scale analysis evaluated the technical and economic potential of the hydrogen and fuel cells industry in diverse future energy scenarios. The team evaluated the economic potential of grid-integrated electrolysis at various future price points of electricity and natural gas and given R&D that lowers the cost of electrolyzer and fuel cell technologies. The team also estimated how future markets for “otherwise curtailed electricity” could increase renewables penetration on the grid.
- **Connected Loads** (ORNL) [BTO] – Develop and evaluate grid connected equipment that increase the operational flexibility of loads in buildings to improve grid-responsive behavior and system efficiencies.
- **dsGrid** (NREL) [EERE] – is a data collection framework to model highly spatial and temporally resolved energy demand by end-use and sector. dsGrid will enable analysis to more accurately identify how storage technologies capabilities can be used to meet load and their potential value propositions, especially as predicted load changes in potential future scenarios.
- **Distribution System Research Roadmap** (PNNL, NREL, LBNL) [SPIA] – Develop a research roadmap to guide future EERE investments in distribution system and DER analyses, identifying high-priority research areas that are scalable and can be leveraged for multiple purposes.
- **State and Local Planning for Energy (SLOPE) Platform** (NREL) [EERE] – Tool to enable more data-driven state and local energy planning by integrating dozens of distinct sources of energy efficiency, renewable energy, and sustainable transportation data and analyses into an easy-to-access online platform that more effectively supports state and local energy planning and decision making.
- **Energy Storage: Thermal Management to Help Mitigate Cycling Damage in Coal-Fired Power Plants** (NETL) [FE] – Understand state of energy storage technologies applicable for deployment at fossil-fueled power plants and to develop approaches that enable the estimation of cost and

value potential of energy storage technologies that augment fossil plant performance and economics.

Transportation and Cross-Sectoral Issues

- **HELICS + Grid + Transportation** (PNNL, ANL) [OE] – The Use Case will evaluate the interdependence of electric and transportation networks specifically, the work studies/quantifies how to efficiently utilize the fleet of electric vehicles (EVs) for power system restoration following a disaster event.
- **Behind-the-Meter Storage (BTMS)** (NREL) [EERE] – This research is targeted at developing innovative energy storage technology specifically optimized for stationary applications that will enable extreme fast charging of EVs, allow for enhanced, grid-interactive, energy efficient buildings coupled with photovoltaic resources, while minimizing grid impacts. Major metrics: 1) Levelized cost of ownership (LCO) (also known as minimum sustainable price (MSP)), levelized cost of energy (LCOE), and profit; related to payback period and return on investment (ROI) to the system owner, including beyond LCOE project implications; 2) Total system energy use (efficiency) to meet varied energy demands from the building and EV charging; 3) Resiliency in terms of grid backup time (duration for supporting 100% of the loads and critical loads); and 4) Quantified daily load flexibility, both in terms of power and energy.
- **American-Made Challenges Prize Program** (NREL) [EERE] – This prize program structure can easily be leveraged and customized for the Energy Storage Grand Challenge. We can help with prize platform interface, data ingestion, review/judging of submissions, custom submission process, communications strategies/materials, prize payments, network building connections, etc.
- **Lithium Ion Battery Recycling** (ORNL) [EERE] – Establish a Center to develop and scale-up new processes to enable direct recycling of multiple battery materials (cathode, anode, salts) for current and future batteries.
- **POLARIS New Cities Modeling** (ANL) – Develop baseline models for the Atlanta, Austin, and Detroit Metropolitan Regions using the POLARIS SMART Mobility Workflow, in order to demonstrate mobility energy productivity results for common cities between both SMART workflows.
- **Hydrogen Storage (HyMARC)** (LBNL) [HFTO] – This project is part of the large multi-lab DOE Hydrogen Materials-Advanced Research Consortium (HyMARC). The project is ongoing, with the role of conducting techno-economic analysis of incumbent and new bulk (not onboard storage) hydrogen storage and transportation technologies. The levelized hydrogen delivery cost is estimated for different market scenarios for a range of technologies, including adsorption systems using metal organic frameworks, high pressure systems, liquid organic hydrogen carriers, and cryogenic liquid hydrogen. In the first two years, the objectives of the project were to: (1) develop an adsorption process model and simulate the performance of a fixed-bed tube trailer for bulk hydrogen transportation, using experimental and simulated data for a range of sorbent carrier materials; and (2) identify opportunities for cost-reduction given select operation and market conditions, and develop target ranges for viable performance.
- **Optimizing Urban Transportation Systems Energy Using Large-Scale Simulation and Machine Learning** (ANL) [LDRD] – The objective is to develop a new tool to allow the automotive and electric power industry to locate, size, and design control for a PEV fast charging infrastructure

that maintains both economic viability and grid reliability while leveraging connected EV storage to increase system resiliency adding to the energy security of the United States.

- **Reversible Fuel Cells for H_2 Energy Storage Systems** (LBNL) [EERE] – Unitized reversible fuel cells, together with hydrogen storage, could form an energy storage system that can provide long term energy storage that is cost competitive with other technologies. The project objective is to investigate the competitiveness of RFCs for energy storage in a few key applications as a function of use-phase conditions and parametric cost assumptions. The project will determine technical targets for reversible fuel cells with a focus of on large scale energy storage for grid support, and the project will develop a parametric cost model for RFC-based H_2 storage.
- **Storage Manufacturing Hurdles** (NREL) [EERE] – Identify technology that has high impact potential and evaluate the manufacturing cost to identify research areas that would impact adoption.
- **Critical Materials Recycling** (ANL) [EER] – This work couples a chemical separations process model with integrated facility economic models to assess metals recovery and rare earths separation from spent nickel-metal hydride batteries, illustrating the significance of parametric uncertainties.
- **Storage Technology Review** (NREL) [EERE] – For promising storage technology, write a technology review for each technology, specifically identifies the manufacturing R&D activities, opportunities, and pathways forward.
- **National DCFC Economics Map** (NREL) [EERE] – National analysis of DCFC economics optimized for minimum life cycle cost when co-located with buildings, solar, and stationary storage. This research informs economically feasible utility rate structures, locations, and technology combinations for DCFC deployment.

Foundational Policy and Valuation Needs

Current and Future Cost and Performance Data

- **Energy Storage Futures** (NREL) [EERE] – Comprehensively examines the potential role of storage in the power sector, including lithium-ion and flow batteries, compressed air, pumped-hydro, and seasonal storage, across a range of potential future cost and performance scenarios out to 2050. Investigate scenarios including a range of possible storage characteristics and cost projections and a range of renewable energy levels using utility-scale electric sector modeling (capacity expansion and production cost modeling) in conjunction with distributed storage deployment modeling.
- **Long-Duration Storage** (NREL) [EERE] – This study is examining technology and system options to provide long-duration storage for the electricity grid at the national bulk-power level. It is evaluating the scale of the long-duration storage challenge and the costs and tradeoffs faced by candidate technologies to meet these challenges. The study will cover a broad range of technology and system options, with a particular focus on hydrogen systems as they were recently identified as the likely low-cost leader and will consider the tradeoffs of these options with shorter-term storage, transmission, or other approaches.
- **Annual Technology Baseline** (NREL, NETL) [EERE, FE] – Tracks current cost and performance metrics for power sector technologies and provides future cost and performance projections under a range of R&D scenarios.

- **Energy Storage Cost Characterization** (PNNL, ANL, ORNL) [EERE, OE] – Defines and evaluates cost and performance parameters of six battery energy storage technologies (BESS) (lithium-ion batteries, lead-acid batteries, redox flow batteries, sodium-sulfur batteries, sodium metal halide batteries, and zinc-hybrid cathode batteries) and four non-BESS storage technologies (pumped storage hydropower, flywheels, compressed air energy storage, and ultra-capacitors).
- **Relationship between Cost Reduction and Deployment for Vehicle and Stationary Storage** (LBNL) [EERE, OE] – Development of framework and analysis of relationship between cost reduction, deployment, and storage technology paths across vehicle and stationary storage.
- **PV + Storage System Cost Benchmarking** (NREL) [EERE] – Bottom-up system cost modeling, including standalone battery storage, and storage plus PV in the residential, commercial, and utility sector. Also benchmarking the Levelized Cost of Solar plus Storage (LCOSS).
- **Tracking Hybrids: Utility-Scale and Behind the Meter** (LBNL) [EERE] – Within the context of annual solar and wind reports and related data collection, LBNL collects data on development trends and pricing for utility-scale wind and solar battery hybrids. Additionally, LBNL has a project that will assess trends and costs of behind-the-meter solar + storage systems.
- **Solar-to-Methane** (NREL) [EERE] – Identify specific performance and cost targets to enable a glidepath from today's capabilities to operational scenarios based on expected future performance for a Solar PV-PEM Electrolyzer–Biomethanation Reactor system.
- **Annual Hydropower Market and Trends Report** (ORNL) [EERE] – Track 1) status of PSH projects in the development pipeline (from application for a preliminary permit to cancelled or operational), 2) trends in U.S. PSH performance and revenue, 3) policy and market drivers for PSH development.
- **Alternative CAES Technology Using Depleted Unconventional Gas Wells and Subsurface Thermal Energy Storage** (NREL) [EERE] – Understanding sedimentary reservoir response and performance during compressed air injection and production, characterizing feasible design conditions, designing system operating conditions to maximize energy storage and recovery, and performing techno-economic analysis to determine technology cost.
- **Lithium Ion Battery Analysis Project** (NREL) [EERE] – The Lithium Ion Battery Analysis (LIBRA) project uses system dynamics modeling to understand the system levers and bottle necks to LiB recycling; LIBRA simulates the build out of the LiB recycling industry in response to anticipated demands, resource availability, and policies.
- **Alternative CAES Technology Using Depleted Unconventional Gas Wells and Subsurface Thermal Energy Storage** (NREL) [EERE] – Understanding sedimentary reservoir response and performance during compressed air injection and production, characterizing feasible design conditions, designing system operating conditions to maximize energy storage and recovery, and performing techno-economic analysis to determine technology cost.

Valuation Methodologies

- **Locational Value of DERs** (LBNL) [EERE] – Assessing the locational value of DERs to cost-effectively meet generation, transmission, and distribution needs. Focus on the distribution system, though using an integrated approach to assess DER locational value electricity system-wide.
- **Valuation and Operational Performance of Solar + Storage** (NREL) [EERE] – This project will develop improved methods for evaluating and comparing different solar plus storage

technologies. It will examine the operation of different solar plus storage technologies and configurations including optimal coupling of PV plus batteries and inverter loading ratio/solar multiple. Major areas include PV plus batteries: varying system architectures, DC/AC coupling, inverter loading ratios, etc.; CSP plus thermal energy storage: advanced cycles, flexible operations.

- **Valuing PVEE in Buildings** (NREL) [EERE] – Identify how integrating PV with flexible building loads and energy storage can maximize the value of PV.
- **Distributed PV plus Storage Approaches** (NREL) [EERE] – Analysis to understand the opportunities and challenges related to behind-the-meter PV and storage under different rate structures.
- **Integrated Hydropower and Energy Storage Systems** (INL, ANL, NREL) [EERE] – This project is focused on articulating the value proposition of integrating energy storage systems with Run of River Hydropower Plants.
- **Valuation Guidance and Techno-Economic Studies for Pumped Storage Hydropower** (ANL, INL, NREL, ORNL, and PNNL) [EERE] – The goal is to develop a detailed step-by-step valuation guidance and apply it to two competitively selected PSH sites to test the valuation methodology and assist the developers in understanding the value streams available from their projects.
- **Grid Services and Technology Evaluation** (multiple labs) [GMLC] – Develop a valuation framework for grid services and technologies that guides users to the proper methods to use for valuation and defines the common terminology for assumptions and sharing results.
- **Industrial Storage Value** (NREL) [EERE] – Analyze the technical and economic potential for energy storage and electrification of industrial process heat on the industrial and power grid sectors.
- **A Framework and Tools to Assess the System-Level Relationships Between Energy Efficiency and Demand Response** (LBNL) [EERE] – This project will develop a new integrated valuation methodology based on energy efficiency (EE) and demand response (DR) measure load shapes and regional electricity features to assess the load and economic relationships of EE and DR.
- **Devices Providing Grid Services (HVAC and Refrigeration)** (ORNL) [EERE] – Development of a comprehensive and transparent framework to value the services and impacts of grid-related technologies.
- **Extreme Fast Charge Cell Evaluation Project** (NREL, INL, ANL) [EERE] – With growing interest in achieving full EV charging in as fast as 5 to 10 minutes, NREL is partnering with DOE, Argonne National Laboratory (ANL), Idaho National Laboratory (INL), and industry stakeholders to identify how extreme fast charging can become a reality.

Improved Tools

- **Improving Representation of Storage in Capacity Expansion Models** (NREL) [EERE] – Develop new capabilities for representing the cost and value of storage in the ReEDS long-term planning model. Focus on improving value for capacity, energy, and ancillary services and continued battery cost and performance projections. When complete, use updated model to examine interactions of storage with scenarios of high penetrations of VRE.
- **System Advisor Model Battery Modeling and Improvements** (NREL) [EERE] – This project enables a detailed battery model with robust lifetime modeling in conjunction with PV systems.

- **System Advisor Model CSP and Thermal Storage Modeling** (NREL) [EERE] – Ongoing enhancements and updates for thermal storage both connected to a CSP collector.
- **Conceptual Design for Thermal Energy Storage Systems Using IDEAS** (NETL) [FE] – Down-select the best thermal energy storage system design using deterministic optimization techniques within the IDEAS model.
- **DER-CAM** (LBNL) [OE] – DER-CAM provides DER planning solutions to supply all energy services required by a building/microgrid, while optimizing the electric and heat energy flows to minimize costs and environmental footprint. DER-CAM finds the optimal solution that balances the cost of additional DER capacity and operation and the value of lost loads that would otherwise occur during these interruptions. This process considers different load prioritizations and definitions, including critical and noncritical loads. Outputs include optimal DER investment portfolios, sizing, placement within the microgrid topology, and the dispatch of all DERs present in the solution, including any load management decisions such as load-shifting, peak-shaving, or load prioritized curtailments in the event of outages.
- **HydroWIRES Topic B: Enhancing the Representation of Conventional Hydropower Flexibility Production Cost Models** (ANL) [EERE] – This project improves the representation of hydropower plants in Production Cost Models (PCMs) in terms of plant utilization and the valuation of hydropower resources in grid operations.
- **Improving Hydropower and PSH Representations in Capacity Expansion Models** (NREL) [EERE] – Long-term planning tools have difficulty representing detailed hydropower operating characteristics, which depend not only on technological specifications but also on water management practices and regulations. This work will fill that gap by developing new ways to represent hydropower resource, technology, and operational characteristics in electric sector capacity expansion models and implementing them in the open-source version of the ReEDS model. It will also include the first every comprehensive national resource assessment of pumped storage hydropower.
- **Cost Data Collection and Modeling for Hydropower** (ORNL) [EERE] – Develop capabilities for techno-economic analysis of hydropower technologies at the component and facility level. Current integrated model has capabilities to evaluate conventional hydropower technologies and is being enhanced for the evaluation of innovative options.
- **REopt Lite Energy Storage Modeling** (NREL) [EERE] – Ongoing enhancements of the free, publicly available web tool and API for integrated PV, storage, wind, and CHP economic design and dispatch through improved battery degradation modeling in the context of economic optimization, addition of thermal energy storage, and integration of electric vehicle charging.
- **CAEBAT** (NREL) [EERE] – Develop multi-scale multi-dimensional models that span the length scales from atomistic to grid that provides insights into the electrical, thermal, and life performance of battery systems.
- **Mechanical Electrochemical Thermal Models** (NREL) [EERE] – First model to simultaneously solve the mechanical, electrochemical, and thermal events that occur during battery abuse conditions—nail penetration, crush, internal short circuit, etc.
- **Battery Lifetime and Simulation Tools (BLAST)** (NREL) [EERE] – Battery lifetime and simulation tool for vehicle and grid applications.

- **Core BatPaC Development** (ANL) [EERE] – This project continues the development of the Battery Performance and Cost Model by enhancing the functional capabilities of the tool to facilitate the design and analysis of lithium ion batteries (and similar chemistries).
- **EverBatt** (ANL) [VTO] – EverBatt is a closed-loop model used to estimate cost and environmental impacts throughout a battery's lifespan.
- **Battery Size Optimizer** (LBNL) [LDRD] – Developed a model that takes actual or predicted second-by-second or minute-by-minute generation and load data combined with battery aging data to properly size and cost the battery for any application.
- **Technical Resilience Navigator** (TRN) (NREL, PNNL) [EERE] – The TRN enables users to assess risk to critical functions and account for resilience priorities and other factors important to their site. Users identify risk drivers and resilience gaps at their site that must be addressed by resilience solutions and prioritized according to risk-reduction potential, cost, and how well they address other key site priorities.

Market and Utility Operations Information

- **Impacts of Solar Export Credit Rates on PV + Storage Economics and Alignment of Value** (LBNL) [EERE] – Replacing net energy metering policy with tariffs that incentivize self-consumption may not fully align with bulk or distribution grid needs. As distributed battery storage adoption increases, it will be important to align residential rates with grid need to ensure alignment of storage operation with grid need to maximize battery value.
- **Implications of Rate Design for Economics of Behind-the-Meter Storage and PV + Storage** (LBNL) [OE] – Inform regulators on policy objectives related to rate reform and storage deployment by exploring how proposed changes in rate design may impact the customer economics of storage.
- **Pumped Storage Hydro Fast Commission Challenge** (ORNL) [EERE] – The key outcome is identification of primary development barriers and solution categories that can be used to guide future research into developing high-impact technology innovations. To assess PSH project time, cost, and risk drivers and technological improvement opportunities, important categorical areas—Civil Works, Engineering, and Equipment—were identified.
- **Hydropower RAPID Toolkit** (NREL) [EERE] – Data collection on licensing timelines for pumped storage hydropower projects.
- **GMLC Technical Assistance to States on Grid-Interactive Efficient Buildings** (multiple labs) [GMLC] – This project will provide direct technical assistance to state energy offices and public utility commissions in geographically diverse states. We will deliver near-term successes by leveraging: (1) the National Association of State Energy Officials (NASEO) and National Association of Regulatory Utility Commissioners (NARUC) Grid-interactive Efficient Buildings Working Group (Working Group) to prioritize and effectively deliver technical assistance needs and (2) new lab research on Grid-interactive Efficient Buildings and demand flexibility. This technical assistance will enable states to take advantage of innovations in building and grid technologies to unlock grid services that buildings can provide for the bulk power system and distribution system.
- **ISO/RTO Technical Assistance** (ANL/NREL/LBNL/SNL) [GMLC] – Provide technical assistance and support to ISO/RTOs and their stakeholders through robust analysis in response to key

challenges facing the bulk power system during the ongoing grid transformation. One of the proposed areas includes storage.

- **Public Utility Commission Technical Assistance** (multiple labs) [GMLC] – This project will provide technical assistance to state PUCs on any topic included in the Multi-Year Program Plan, including different forms of energy storage, using an annual competitive solicitation process, where the TA engagement will last between 1 and 2 years and be provided by a team of experts from across the Lab complex.
- **Resource Options Analysis for State TA** (LBNL) [OE] – This project will provide technical assistance to state PUCs and state energy offices through the NARUC-NASEO Task Force on Comprehensive Electricity Planning and NASEO-NARUC Grid-Interactive Efficient Buildings Working Group on: (1) critical information gaps; (2) optimizing resource selection for achieving state energy goals including reliability, resilience, security, and affordability; and (3) advancing integrated analyses of all resource options (distributed energy resources, utility-scale generation, and traditional transmission and distribution solutions)—for vertically integrated states, this extends across bulk power systems and distribution systems.
- **Future Electric Utility Regulation** (multiple labs) [GMLC] – The project supports state policymakers and regulators exploring changes to regulatory approaches, utility business models (including product and service offerings), and rate design that balance the interests of customers and utilities with grid modernization goals.
- **Electricity Market Complex Adaptive System** (ANL) [LDRD] – EMCAS is an agent-based model intended to analyze issues of deregulated / restructured energy markets. An EMCAS simulation runs over six decision levels, ranging from hourly dispatching to long-term planning.
- **Distribution System Planning Trainings** (multiple labs) [GMLC] – This project will provide training for state PUCs, SEOs, state utility consumer representatives, and other state decision-makers on best practices in integrated distribution system planning and grid modernization strategies to improve reliability, resilience, and electricity affordability throughout the electricity system. The Statement of Work includes developing a new module on impacts of storage on distribution system planning.

Appendix 5: Energy Storage Cost and Performance Metrics

Energy storage cost and performance metrics are used to assess energy storage technologies' ability to meet the technical and economic requirements of specific use-case applications. Due to the nascent nature of energy storage technologies, a standardized list of cost and performance metrics has yet to become universal. The list of metrics below comes from several detailed reports and highlights key cost and performance metrics, but it is not intended to be comprehensive.[218] The ESGC will continue to work with stakeholders to define and standardize useful cost and performance metrics.

Performance Metrics

- **Black Start Capable** – refers to ability of technology to enable the process of restoring electric power from complete blackout, without relying on an external power source.
- **Calendar Life**[219] (Years) – the number of years an energy storage system can be stored or minimally used while maintaining a high percentage of initial capacity.
- **C-Rate** (C) – charge/ discharge rate of a battery normalized to its maximum capacity.
- **Cycle Life**[220] (Cycles) – the number of charge/discharge cycles an energy storage system can complete while maintaining a high percentage of initial capacity.
- **Cycles Per Day** (#) – the number of times the energy storage system charges and then discharges to a certain depth of discharge (usually 80%) within a 24-hour period.
- **Cycles Per Year** (#) – the number of times the energy storage system charges and then discharges to a certain depth of discharge (usually 80%) over the course of a year.
- **Degradation Factor** (%) – refers to the amount of rated capacity or energy capacity that is lost over time as the components of the system experience wear and tear and/or chemical changes.
- **Depth of Discharge** (%) – represents the ratio of discharged energy (kWh) to usable energy capacity (kWh).
- **Discharge Voltage Variability –** Amount of variation in voltage magnitude caused by spikes, dips, surges, etc.
- **Duration** (Seconds, Minutes, Hours, Days, etc.) – the amount of time a storage system can discharge at its rated power capacity before depleting its energy capacity. For example, a storage system with 1 MW of rated power capacity and 4 MWh of energy capacity will have a storage duration of four hours.
- **Energy Capacity** (kWh) – the maximum amount of stored energy the system can hold.

218 Mongrid, K., V. Viswanathan, P. Balducci, J. Alam, V. Fotedar, V. Koritarov, and B. Hadjerioua. 2019. *Energy Storage Technology Cost Characterization Report* (Technical Report). PNNL – 28866. Pacific Northwest National Laboratory. https://energystorage.pnnl.gov/pdf/PNNL-28866.pdf; IRENA. 2017*. Electricity Storage and Renewables: Cost and Markets to 2030*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf; Connover DR., AJ Crawford, J. Fuller, SN Gourisetti, V Viswanathan. SR. Ferreira, DA. Schoenwald, and DM Rosewater. 2016. *Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems* (Technical Report). PNNL-22010/SAND2016-3078. Pacific Northwest National Laboratory and Sandia National Laboratories. https://energystorage.pnnl.gov/pdf/PNNL-22010Rev2.pdf

219 ABB Inc., ANL RFI Responses

220 ABB Inc., BNL, C4V, Eos Energy Storage, Gridtential Energy Inc., IEEE, Southern Company R&D RFI Responses

- **Energy Density** (kWh/L) – the amount of energy that an energy storage system can store per unit volume occupied by the system.
- **Energy-to-Power Ratio** (KWh/kW) – relationship between energy capacity and rated power capacity in a given application.
- **Footprint**[221] (square feet) – the physical area a storage system requires.
- **Limited Oxygen Index**[222] (%) -- safety metric specific to storage systems with electrolytes that measures the minimum concentration of oxygen in the air that will keep an electrolyte burning. The higher the Limited Oxygen Index, the lower the fire risk.
- **Maximum Operating Temperature** (°) – the maximum temperature at which a storage system can effectively operate.
- **Minimum Operating Temperature** (°) – the minimum temperature at which a storage system can effectively operate.
- **Operational Life** (Years) – the number of years an energy storage system can operate while maintaining its normal cycle rate for its given Use Case.
- **Percent Environmentally-Sensitive Material**[223] (%) – amount of environmentally-sensitive or rare-earth material (such as cobalt or lithium) required to manufacture a given storage system.
- **Power Density** (kW/L) – the maximum available power per unit volume.
- **Ramp Rate** (%/second) – the rate of change of power delivered to or absorbed by an energy storage over time, expressed in megawatts per second or as a percentage change in rated power over time (percent per second).
- **Rated Power Capacity** (kW) – the total possible instantaneous discharge capability of the storage system, or the maximum rate of discharge the storage system can achieve starting from a fully charged state.
- **Recyclability**[224] (%) – weight% of materials in a storage system that may be recycled for post-end-of-life use.
- **Response Time Constrained by Power Conversion System** (Seconds) – the time in seconds it takes an energy storage system to reach 100% of rated power during charge/discharge constrained by technical limits of its power conversion system.
- **Round Trip Efficiency** (%) – the ratio of energy output (kWh) to energy input (kWh) of storage system during one cycle. For battery technologies these refer to DC/DC efficiencies while mechanical-based systems are expressed in AC/AC terms.
- **Self-Extinguishing Time**[225] (s) – safety metric specific to storage systems with electrolytes that measures time for an on-fire electrolyte to put itself out. The lower the Self-Extinguishing Time, the lower the fire risk.

221 Enel Green Power, Redstone Technology Integration, Sacramento Municipal Utility District (SMUD), Technology Management Applications RFI Responses

222 DOE OE Energy Storage Safety Strategic Plan (December 2014); responding to Aestus Energy Storage, Enel Green Power, Energy Vault, Hunt Energy Enterprises LLC, Sacramento Municipal Utility District (SMUD), Stanford University RFI Responses

223 Amber Kinetics, Enel Green Power, Form Energy Inc. RFI Responses

224 Enel Green Power RFI Response

225 DOE OE Energy Storage Safety Strategic Plan (December 2014); responding to Aestus Energy Storage, Enel Green Power, Energy Vault, Hunt Energy Enterprises LLC, Sacramento Municipal Utility District (SMUD), Stanford University RFI Responses

- **State of Charge** (%) – represents the storage systems level of charge and ranges from completely discharged (0%) to fully charged (100%).
- **Theoretical Response Time** (Seconds) – the time in seconds it takes an energy storage system to reach 100% of rated power during charge/discharge or from an initial measurement taken when the system is at rest.
- **Weight**[226] (kg) – how heavy the storage system is.

Development and Deployment (D&D) Metrics

- **Domestic Manufacturing Capacity** (units; MW; MWh; % of global capacity)– the maximum amount, measured either in quantities of energy and power storage capacity (as opposed to number of battery modules or fuel cells) or as a percentage of global capacity (measured in those units), that all U.S. manufacturing facilities could produce in a single month. This does not mean that those facilities are producing this amount every month; it is an estimate of maximum production possible.
- **Manufacturing Readiness Level** (1–10) – measure used for assessing how mature the manufacturing of a product for a technology is and it ranges from a scale of 1 (basic manufacturing issues identified) to 10 (high rate production using efficient production practices demonstrated).[227]
- **Technology Readiness Level** (1–9) – measure used for assessing the phase of development of a technology. It indicates how mature the technology is and ranges from a scale of 1 (basic principle observed to 9 (total system used successfully in project operations).
- **U.S. Global Market-Share** (%) – percentage of global market-share (in $) of a technology comprised of U.S.-owned businesses.
- **U.S. Supply Chain Coverage** (%) – measure of how domestic the supply chain for a storage system is, found by dividing the number of supply chain stages required to manufacture the system located in the U.S. by the total number of supply chain stages for the system.

[226] Aestus Energy Storage, MIT RFI Responses

[227] For additional information see https://prod-ng.sandia.gov/techlib-noauth/access-control.cgi/2010/107595.pdf

Cost Metrics

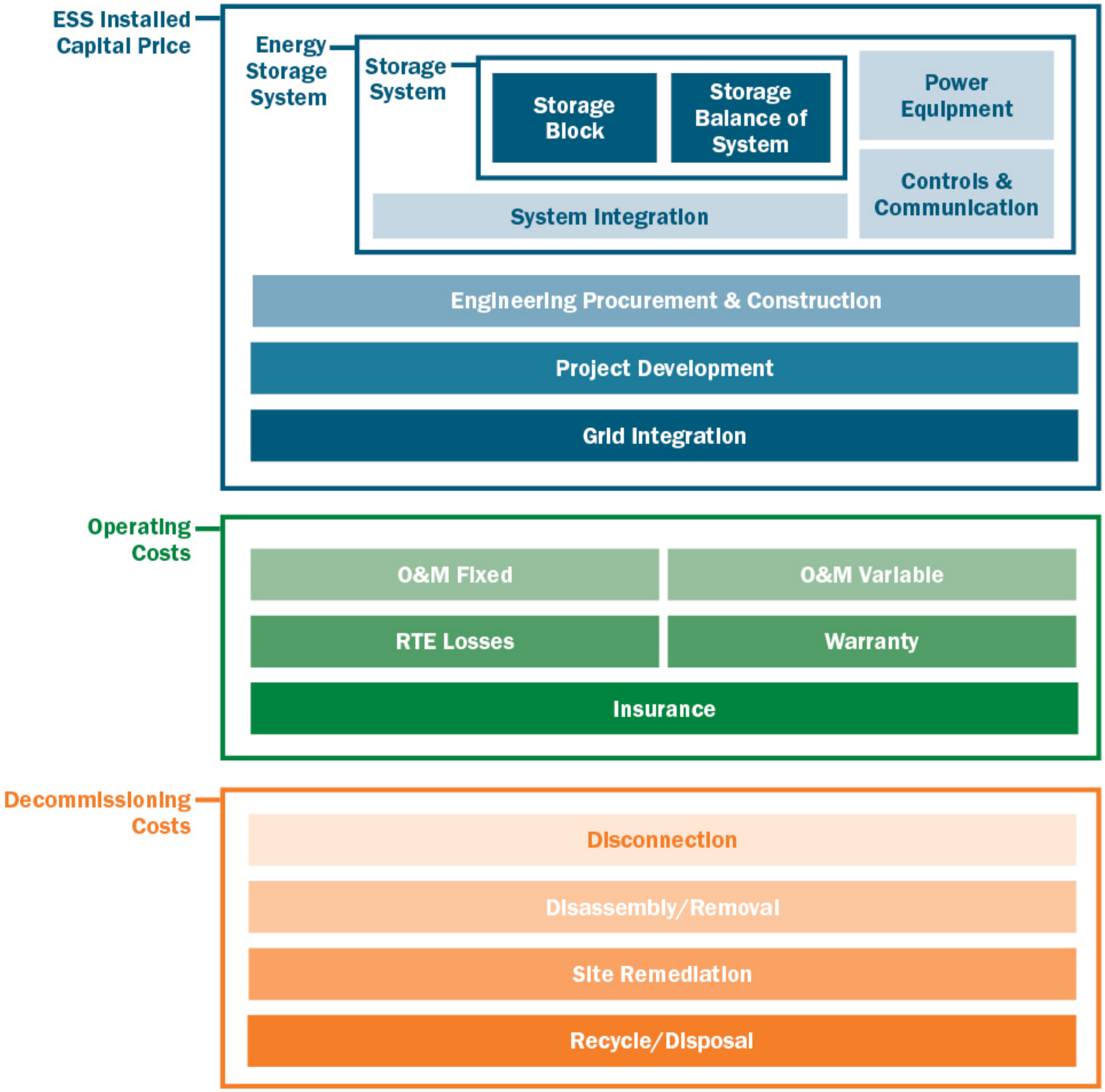

Figure 23. Energy storage cost breakdown

- **Capital Expenditures (CapEx)**
  - **Energy Storage System (ESS) Installed Cost Components**
    - **Storage Block (SB)** ($/kilowatt-hour (kWh)) – this component includes the price for the most basic storage element in the system, expressed in $/kWh. (e.g., for lithium-ion, this price includes the battery module, rack, battery management, system, and is comparable to an electric vehicle pack price).

    - **Storage - Balance of System (SBOS)** ($/kWh) – includes supporting cost components for the SB including container, cabling, switchgear, flow battery pumps, HVAC, and other similar components.
    - **Storage System** ($/kWh) – this cost is simply the sum of the SB and SBOS costs and may be an appropriate level of granularity for some studies.
    - **Power Equipment** ($/kilowatt (kW)) – this component includes bi-directional invertor, DC-DC converter, isolation protection, alternating current (AC) breakers, relays, communication interface, DC-DC converters, software. This is the power conversion system for batteries, the powerhouse for PSH, and the powertrain for CAES.
    - **Controls & Communication (C&C)** ($/kW) – this includes the energy management system for the entire ESS and is responsible for ESS operation. This may also include annual licensing costs for software. The cost is typically represented as a fixed cost independent of E/P.

  - **System Integration** ($/kWh) - price charged by the system integrator to bring sub-components together into a single functional system.
  - **Project Development** ($/kW) – costs associated with permitting, power purchase agreements, interconnection agreements, site control, and financing.
  - **Engineering, Procurement, and Construction (EPC)** ($/kWh) – includes non-recurring engineering costs, construction equipment, as well as shipping, siting, and installation and commissioning the ESS. This cost is reported in $/kWh with weighting based on e/p ratio.
  - **Grid Integration** ($/kW) – cost associated with connecting the ESS to the grid, including transformer cost, metering, and isolation breakers. For the last component, it could be a single disconnect breaker or a breaker bay for larger systems.

- **Operational Expenditures (OpEx)**

  - **Fixed Operations and Maintenance (O&M)** ($/kW-year) – includes all costs necessary to keep the storage system operational throughout the duration of its economic life that do not fluctuate based on energy usage. This includes costs planned for maintenance, labor, and benefits for staff.
  - **Variable O&M** ($/megawatt-hour (MWh)) – includes all costs necessary to operate the storage system throughout its economic life and includes unplanned maintenance costs, and augmentation based on ESS usage patterns. This cost is highly dependent on operation of the ESS and can vary significantly as a result.
  - **Round Trip Efficiency (RTE) Losses** ($/kWh) – this includes HVAC and other auxiliary loads, DC losses, and power conversion system losses. This value is estimated through the cost of the additional electricity purchased in order to achieve a single kWh of throughput due to the losses described.
  - **Warranty** ($/kWh) – fees to the equipment provider for manufacturability and performance assurance of designated lifespan.
  - **Insurance** ($/kWh) – insurance fees to hold a policy to cover unknown and/or unexpected risks. The terms of this cost may depend on vendor reputation and financial strength.

- **Decommissioning Costs**
    - **Disconnection** ($/kW) – costs associated with the removal of ESS interconnection from grid.
    - **Disassembly/Removal** ($/kW) – this includes deconstruction of ESS and components for disposal/recycle.
    - **Site Remediation** ($/kW) – costs required to return the ESS site to either a brownfield or greenfield state.
    - **Recycle/Disposal** ($/kW) – costs associated with separating out recyclable components, shipping to recycling plant, and recycling the material in the plant.
- **Levelized Cost** ($/kWh) – represents the average amount of money per unit of electricity generated that would be required to recover the costs of building and operating an energy storage system plant during assumed financial life and duty cycle. Key inputs include capital expenditures, operational expenditures, financing cost, and utilization factor. Levelized costs are often used to compare the cost effectiveness of energy storage investments.
- **Levelized Cost of Storage** ($/kWh) – the aggregate cost of an energy storage investment over its operation life (including financing costs) divided by its cumulative delivered electricity. While consensus has yet to develop on its exact formulation, LCOS is the most common levelized storage metric.
- **Levelized Life Cycle Costs** ($/kWh) – the total cost of an energy storage investment over its entire life including raw materials, manufacturing, operations, and decommissioning/end of life divided by its cumulative delivered electricity. While more comprehensive, this metric is used less due to the difficulty of obtaining consistent beginning of life (materials and manufacturing) and end-of-life (decommission and recycling) data.
- **Total Cost of Ownership**[228] ($) – Total of all costs related to a storage system, including capital, operational, and maintenance costs.

[228] Lockheed Martin RFI Response

Appendix 6: Current Energy Storage Regulatory Issues

Federal, state, local, and market-level regulations can have a significant impact on how energy storage is valued, operated, and deployed. The list below captures relevant energy storage regulations at the federal and state level that are currently active. Energy storage regulations inside competitive wholesale markets are still in open proceedings and were not included. Local-level regulations related to zoning, safety, and procurement can be important but were excluded due to sheer number of different localities. This list is not intended to be comprehensive or advocate any particular regulation, instead it is supposed to highlight those regulations that may have impact on how policy is operated and valued. The regulations described below come from Pacific Northwest Laboratory's *Energy Storage Policy Database*, Sandia National Laboratories' *Energy Storage Database*, and the National Renewable Energy Laboratory's *Federal Tax Incentives for Energy Storage Systems.*[229]

Table 17. Federal-level energy storage regulations

Entity	Title	Type	Year	Description
FERC	Order 755	Market Participation	2011	Requires organized markets to compensate frequency regulation resources (including storage) based on their capacity and actual performance.
FERC	Order 784	Market Participation	2013	Requires transmission operators to consider speed and precision of providing ancillary services on a non-discriminatory basis. Specifically forces operators to acknowledge energy storages ability quickly and precisely mitigate frequency disturbances and other grid interruptions.
FERC	Order 792	Market Participation	2013	Revises the pro forma Small Generator Interconnection Procedures and pro forma Small Generator Interconnection Agreement to include energy storage devices.
FERC	Order 841	Market Participation	2018	Instructed each regional grid operator to remove barriers for energy storage technologies participating in capacity, energy, and ancillary service markets. Each RTO/ISO must establish participation models for energy storage technologies.
FERC	Order 845	Market Participation	2018	Revises the definition of "generating facility" in the pro forma Large Generator Interconnection Procedures and pro forma Large Generator Interconnection Agreement to explicitly include electric storage resources (larger than 20 MW) and allow interconnection service lower than the nameplate capacity of the generating facility.
IRS	Investment Tax Credit	Tax	2016	If a battery storage system is owned by a (private) tax paying entity and coupled with a photovoltaic system, it is eligible for up to a 30% investment tax credit. The system must charge at least 75% of the time from the PV system and is credited proportionally so a system that charged 80% of the time from PV would receive a 24% credit and a system that charged 100% from the PV subsystem would receive all 30%. Standalone energy storage systems are currently ineligible to receive the investment tax credit.
IRS	Modified Accelerated Cost Recovery System	Tax	2016	If an energy storage system is owned by a private (tax-paying) entity, it is eligible for 7-year MACRS depreciation schedule, an equivalent reduction capital cost reduction of 20%. If the energy storage is coupled with a photovoltaic system, the combined system is eligible for 5-year accelerated depreciation if the battery is charged 100% of the time using PV. If the combined system is charged using PV more than 75% of the time, it is also eligible for 5-year accelerated depreciation. If the combined system is charged by PV less than 75% of the time, it is eligible for 7-year accelerated depreciation.

[229] Pacific Northwest National Laboratory. Energy Storage Policy Database. https://energystorage.pnnl.gov/regulatoryactivities.asp; Sandia National Laboratories. Energy Storage Database. https://www.sandia.gov/ess-ssl/global-energy-storage-database-home/; National Renewable Energy Laboratory. *Federal Tax Incentives for Energy Storage Systems*. https://www.nrel.gov/docs/fy18osti/70384.pdf

Table 18. State-level energy storage regulation

Entity	Type	Title (Year)	Description
Arizona	Utility	E-01345A-15-0182 (2016)	Developed a $4 million program to use residential-sited storage for demand response and load management.
	Incentives	E-01345A-16-0036 (2017) EA-01345A-16-0123 (2017)	Implemented rates to fund a $2 million annual program designed to assist large commercial customers to deploy energy storage systems for peak demand reduction.
California	Procurement	AB 2514 (2013) AB 2868 (2016)	Deploy 1,325 MW of Energy Storage by 2020 Deploy 500 MW of distribution connected storage.
	Utility	15-03-011 (2018) 19-09-043 (2019)	Requires utilities to include the full economic value of energy storage in resource planning by evaluating multiple benefits. Requires storage to be included in modeling related to the Effective Load Carrying Capability values, which is used by the California Public Utilities Commission in bid ranking and selection.
	Incentives	Self-Generation Incentive Program (2016)	Funded $378 million for customer-sited energy storage projects from 2017-2021.
		19-01-030	Enabled net metering for facilities that have energy storage as long as the power control-based solutions prevent the storage device from charging from or exporting to the grid.
		AB 1144	Allocates 10% of annual collections for the Self-Generation Incentive Program to be used for energy storage installation at critical facilities in high fire threat districts.
Colorado	Procurement	HB 18-1270 (2018)	Directs PUC to develop mechanisms for utilities to procure energy storage systems.
	Utility	C18-1124	PUC requires utilities to include energy storage in resource planning processes.
		SB 19-236	Utilities must file distribution system plans which evaluate energy storage.
	Utility	SB 18-009	Customers have right to install and interconnect energy storage systems. PUC must develop interconnect rules for customer-sited storage projects.
Hawaii	Utility	Order 34514 (2017)	Incents utilities to invest in renewable generation-enabling infrastructure (including energy storage) by allowing them to use accelerated cost recovery.
	Incentives	Order 34924 (2017)	Introduced the NEM Plus Program which allows current net meriting customers to add energy storage to their existing systems, through energy output is not allowed to the export grid.
	Incentives	Order 33258 (2015)	Created the Customer Self-Supply Option and the Smart Export Program to incent customers to pair solar installations with energy storage.
Maine	Utility	LD 1614 (2019)	Required the state to study economic, environmental, and energy benefits of energy storage.
	Utility	LD 1181 (2019)	Creates a position for non-wires alternatives coordinator to work with Office of the Public Advocate.
	Incentive	LD 1711 (2019)	PUC can develop incentives to support DERs with energy storage subsystems.
Maryland	Incentive	HB 1414 (2017)	Requires energy storage be part of study of state's Renewable Portfolio Standard.
	Incentive	State Income Tax Credit	Energy storage systems of up to $5,000 for residential customers and 30% (up to %75,000) for commercial customers.
	Demonstration	SB 573 (2019)	Directs the state's investor-owned utilities to develop energy storage pilot projects that explore different ownership models and Use Cases.
Massachusetts	Procurement	Chapter 188, Acts of 2016	Requires 200 MW of energy storage by 2020. Requires 1,000 MW of energy storage by 2025.

Entity	Type	Title (Year)	Description
		Chapter 227, Acts of 2018	
	Utility	Chapter 227, Acts of 2018	Requires Department of Energy Resources to consider proper valuation of energy storage in planning and procurement processes.
		HB 2496 (2019)	Adds battery storage to the definition of Green Energy Technology, used in contracting for public build renovations.
	Demonstration	ACES RFP (2017)	The Advancing Commonwealth Energy Storage program awarded $20 million in grants to 26 storage projects in 2017 to demonstrate to Use Case applications.
	Incentive	DPU-17-146-A (2019)	Allows solar plus storage systems to participate in net metering as long as the system cannot charge or export to the grid.
Minnesota	Utility	Statute 216B.2422 (2019)	Requires energy storage systems to be evaluated in utility resource planning processes.
	Demonstration	Statute 216B.16 (2018)	Allows utilities to recover the cost of energy storage pilot projects.
Missouri	Utility	EO-2020-0044 (2019)	Requires utilities to analyze energy storage in their integrated resource plans and establish a distributed energy resource database.
Nevada	Procurement	SB 204 (2017)	Directs the PUC to investigate and establish whether the state should hold biennial storage adoption targets. Proceedings are still underway.
	Incentive	SB 145 (2017)	Expanded the state's solar Energy Systems Incentive Program to include payment for electric utility customers to install energy storage systems.
	Utility	AB 405 (2017)	Establishes right for consumers to interconnect energy storage systems in a timely manner, subject to reasonable technical and safety standards
New Hampshire	Demonstration	Order 26,209 (2019)	Allow utilities to own energy storage pilot systems on residential customer premises.
	Incentive	Order 26,209 (2019)	Allows for customers to use net metering for their storage systems including charging and discharging with the grid.
		HB 464 (2019)	Allows municipalities to adopt a property tax exemption for electric storage systems.
New Jersey	Procurement	AB 3723 (2018)	Specifies the deployment of 600 MW of energy storage by 2021 and 2,000 MW of energy storage by 2030.
	Utility	AB 3723 (2018)	Requires the PUC to identify the optimal uses for energy storage as well as cost and benefits for acquiring it.
New Mexico	Utility	Case 17-0022-UT (2017)	Requires Utilities to included energy storage in resource planning processes.
New York	Procurement	Case 18-E-0130 (2018)	Specifies the adoption of 1.500 MW by 2025 and 3,000 MW by 2030.
	Demonstration	Reforming Energy Vision (2015)	The REV program has an open call for demonstration projects designed to explore different Use Cases and ownership models.
	Incentives	Case 15-E-0751 (2017)	Implemented a hybrid tariff for four configurations (including energy storage) that only provides value for systems that inject renewable energy into grid.
		Case 17-E-0594 (2017)	Creates financial assistance for back-up power assistance for customers with life-sustaining equipment in Western New York and Finger Lakes.
North Carolina	Utility	HB 329 (2019)	Created regulatory program to manage end-of-life issues for battery systems.
		Docket E 100 (2019)	Enables grid interconnection for add-on storage systems so long as the storage system doesn't increase the total output above the original generation unit's capacity.
		EO No. 80 (2018)	Required Department of Environmental Quality to develop a Clean Energy Plan that included Energy Storage.
Oregon	Procurement	HB 2193 (2015)	Requires the state's two largest investor owned utilities to install 5 MWh each by 2020 and up to 1% of the 2014 peak load.
	Utility	UM 1751 (2015)	Requires PUC establish analytical guidelines for utilities to assess energy storage in their planning processes.

Entity	Type	Title (Year)	Description
	Incentive	HB 2618 (2019)	Establishes rebate program for solar and solar plus storage systems.
South Carolina	Incentive	HB 3659 (2029)	Allows project with energy storage to use net metering if the storage device only charges from an on-site renewable resource.
Texas	Utility	SB 1012 (2019)	Specifies that municipal and cooperative utilities that own and operate energy storage equipment do not have to register as a power generation company.
Utah	Demonstration	SB 115 (2016)	Authorizes the PUC to approve energy storage demonstration projects.
Vermont	Utility	HB 133 (2019)	Clarifies that energy storage facilities of 500kW or more must receive a certificate of public trust before constructed.
	Incentive	Act 53 (2017)	Made energy storage an eligible resource for funding through the Vermont Clean Energy Development Fund.
Virginia	Utility	SB 966ER (2018)	As part of the Electric Distribution Grid Transformation Project, utilities need to identify energy storage and other investments to increase grid reliability and security.
		HB 1760 (2017)	Streamlines lines regulatory approval process for pumped storage hydro projects.
	Demonstration	SB 966ER (2017)	Established a pair of pilot program for investment in energy storage systems between 10 – 30 MW.
	Incentive	SB 1285ER (2017)	Reauthorized the Virginia Solar Energy Development and Energy Storage Authority.
Washington	Utility	UE-151069 (2017) U-161024 (2017)	Directs utilities to equitably consider energy storage in resource planning and procurement processes.
	Demonstration	Clean Energy Fund (2013)	Provided $14.3 million in matching funds for utilities to deploy four utility-scale energy storage projects to test different Use Cases.

The ESGC is a crosscutting effort managed by DOE's Research Technology Investment Committee (RTIC). The Energy Storage Subcommittee of the RTIC is co-chaired by the Office of Energy Efficiency and Renewable Energy and Office of Electricity and includes the Office of Science, Office of Fossil Energy, Office of Nuclear Energy, Office of Technology Transitions, ARPA-E, Office of Strategic Planning and Policy, the Loan Programs Office, and the Office of the Chief Financial Officer.

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